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Geology and hydrogeology of the Megalopolis Basin, Peloponnese, Greece

GEOLOGY AND HYDROGEOLOGY OF THE
MEGALOPOLIS BASIN
PELOPONNESE, GREECE

by

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Upper Cretaceous limestones, the major aquifer in the area.

View of the Megalopolis basin, taken from the west. The power station is seen in the centre of the photograph and the open lignite mine is just visible to its left.

VOLUME II

HYDROGEOLOGY

LIST OF CONTENTS

VOLUME II: HYDROGEOLOGY

PART II:	HYDROLOGY		page
CHAPTER 7	CLIMATE		
	7.1	Introduction	175
	7.2	Precipitation	176
	7.2.1	Annual rainfall	177
	7.2.2	Monthly rainfall	188
	7.3	Evapotranspiration	191
	7.3.1	Air temperature	194
	7.3.2	Relative humidity	198
	7.3.3	Winds	199
	7.4	Conclusions	202
CHAPTER 8	CATCHMENT OF THE ALFIOS RIVER		
	8.1	Introduction - description of the Alfios catchment and drainage system	204
	8.1.1	Factors controlling the development of the catchment and drainage system	206
	8.1.2	Patterns of development of the drainage system	211
	8.2	Total rainfall	213
	8.3	Infiltration	218
	8.4	Run-off	223
	8.4.1	Total run-off of the Alfios river	223
	8.4.2	Analysis of the flow character of the Alfios	232
	8.4.3	Flow character of the major tributaries	240
	8.5	Hydrological balance of the Alfios catchment	246
	8.6	Conclusions	252
PART III:	HYDROGEOLOGY		
CHAPTER 9	HYDROSTRATIGRAPHY		
	9.1	Introduction	255
	9.2	Hydrolithological description of the geological formations occurring in the study area	258

page

CHAPTER 10 GROUNDWATER OCCURRENCE IN THE BASIN OF MEGALOPOLIS - CONTRIBUTION TO THE KYPARISSIA FIELD

10.1 Introduction 269

10.2 Aquifers on the western and north-western sides of the basin 271

10.3 Aquifers on the south-western, southern and south-eastern sides of the basin 275

10.4 Aquifers on the eastern side of the basin 276

10.5 Aquifers on the northern and north-eastern sides of the basin 278
10.5.1 Introduction - Definition of their extent 278
10.5.2 Percolation of groundwater to the deeper aquifer system 279
10.5.3 The Kefalovrisi and Korbitsi springs 282
10.5.4 The Panagia and Opiste Panagia springs 285

10.6 Conclusions 289

CHAPTER 11 GROUNDWATER OCCURRENCE IN THE KYPARISSIA FIELD

11.1 Introduction 293

11.2 Aquifers in the terrace gravel-bodies 295

11.3 Aquifers in the basin sediments of the Apiditsa and Choremi stages 297

11.4 Karstic aquifers 302
11.4.1 Introduction 302
11.4.1.1 Results of previous investigations 302
11.4.1.2 Present interpretation 308
11.4.2 Geological and geophysical determination of the extent of the karstic aquifers 309
11.4.3 Hydrogeological extent of the karstic aquifers 311
11.4.3.1 Introduction 311
11.4.3.2 Form of the piezometric surface water table 313
11.4.3.3 Groundwater level fluctuations 316

11.4.4 Hydrochemical extent of the karstic aquifers 319

11.5 Conclusions 319

page

CHAPTER 12 FLOW CHARACTERISTICS AND HYDRAULIC PROPERTIES OF THE KARSTIC AQUIFERS OF THE KYPARISSIA FIELD

12.1	Aquifer No 1	323
12.1.1	Introduction	323
12.1.2	Sources of recharge	324
12.1.3	Discharge	329
12.1.4	Groundwater levels	331
12.1.4.1	Well hydrographs	331
12.1.4.2	Piezometric maps	354
12.1.5	Pumping tests	369
12.1.5.1	Introduction	369
12.1.5.2	Methods of pumping test analyses	370
12.1.5.3	Results of previous pumping tests	376
12.1.5.4	Interpretation of the pumping tests	379
12.2	Aquifer No 2	393
12.2.1	Introduction	393
12.2.2	Groundwater levels	395
12.2.2.1	Well hydrographs	395
12.2.2.2	Groundwater level contour maps	399
12.3	Aquifer No 3	409
12.3.1	Introduction	409
12.4	Aquifers No 4,5 and 6	413
12.5	Conclusions	415

PART IV: HYDROCHEMISTRY

CHAPTER 13 INTRODUCTION 418

13.1	Physical and chemical parameters	422
13.2	Major ion hydrochemistry	430

CHAPTER 14 AREAL VARIATION IN WATER CHEMISTRY

14.1	Karstic aquifer hydrochemistry	440
14.2	Spring hydrochemistry	457
14.3	Alfios river hydrochemistry	466
14.4	Hydrochemistry of the clastic aquifers	475
14.5	Correlations between the various water types	477
14.6	Variation of water quality with time	491
14.7	Conclusions	495

page

PART V: CONCLUSIONS

CHAPTER 15 CONCLUSIONS 497

References 504

APPENDICES

Appendix Ia Mean monthly and mean annual precipitation (1962-77) 509

Appendix Ib Mean monthly and mean annual precipitation (1962-84) 510

Appendix Ic Annual and mean annual precipitation (1962/3-1983/4) 511

Appendix Id Data for calculating the precipitation equations and correlation coefficients 512

Appendix Ie Monthly and mean annual temperatures (1963-83) 513

Appendix II Mean monthly and mean annual discharge rates of the Alfios river (1961/62-1974/75) 514

Appendix III Groundwater levels in the Kyparissia field (1975-81) 515

Appendix Iv Chemical analyses 519

PART II HYDROLOGY

CHAPTER 7: CLIMATE

7.1 Introduction

Climatological data for the wider area of the Megalopolis basin (Alfios river drainage basin) were provided up to 1962 by only four stations, set up by the Ministry of Public Works and the Ministry of Agriculture. Subsequent to this, around 1962, a large number of stations were established by the Electricity Board (DEH), thus rendering the network more complete.

Unfortunately, the majority of the operating stations are equipped only with rain gauges. A few also have snow precipitation gauges, but the only complete meteorological stations are those at Megalopolis (established 1963) for the narrow basin of Megalopolis and the station at Assea (established 1972), situated in the middle of the Assea sub-basin of the Alfios river catchment to the east of Megalopolis. These provide further data, such as air temperature, in °C, relative humidity and wind direction and velocity. The data provided by the complete meteorological stations of Vytina and Tripolis, situated outside the Alfios river drainage basin, to the north and east of the Megalopolis station respectively, can only be used for comparative studies.

Finally, it should be noted at this point that there is a lack of unity in the collection of the data, due to the fact that the climatological stations in Greece are controlled by four separate bodies. As a result, in order to obtain the monthly and annual mean values for rainfall at a station supervised by the Ministry of Public Works, it is necessary to sum up the daily recordings oneself and these further complications in obtaining accurate data inevitably render the task of studying the hydrology of the region more complex and onerous.

7.2 Precipitation

As outlined above, a relatively dense network of rain gauge stations has been operating within the Alfios river catchment area since approximately 1962. Fourteen of them are still in operation, while five of them fell into disuse in April 1977 (see Table 7.1).

Only a few of them present uninterrupted recordings throughout their period of operation. Usually, just a few monthly values, either scattered or consecutive, are missing from most of the stations but, in a few cases, a whole year's recordings may be unavailable. It was then necessary to supplement these incomplete rainfall records by estimating values that were missing for these stations. The same applied to two other stations, those at Ekklisoula and Kardaras, where a small number of consecutive annual rainfall values were missing (6 and 4 respectively), due to the fact that they were non-operational at these times. Here, the values were needed to calculate the mean annual rainfall over certain periods.

The supplementation of values to complete records of the stations for which records for short periods (ie a month) were missing was done by taking the mean arithmetic value of the rainfall values of two or three adjacent stations which exhibited a similar variation in mean annual rainfall for the corresponding period and using these to provide an estimate. Alternatively, for records missing for longer periods (ie a few months or a year) or for high monthly rainfall values, the normal 'ratio method' was used (Gray, 1970), based on the equation:

$$P_4 = \frac{1}{3}\left[\frac{N_4P_1}{N_1} + \frac{N_4P_2}{N_2} + \frac{N_4P_3}{N_3}\right]$$

where P_4 is the missing rainfall value required for the station; P_1, P_2 and P_3 are the rainfall values recorded for the missing period at different adjacent stations and N_1, N_2, N_3 and N_4 are the long-term normal rainfall values at the same stations. Stations were chosen according to whether they were near to and evenly spaced around the station for which data were lacking but it was also preferable that they should show a similar variation in normal long-term rainfall.

7.2.1 Annual Rainfall

The distribution of rainfall over a certain area is shown by means of isohyetal maps. In order to present the information in this manner, it is necessary first to calculate the mean annual rainfall for a given period at the various stations operating throughout the area.

Binnie (in Wisler and Brater, 1959) studied the periodic variation in precipitation at a given station and determined the average percentage of deviation from an estimated mean rainfall for a limited number of years in relation to the true long-term mean precipitation at this station. His findings are represented graphically in Fig 7.1.

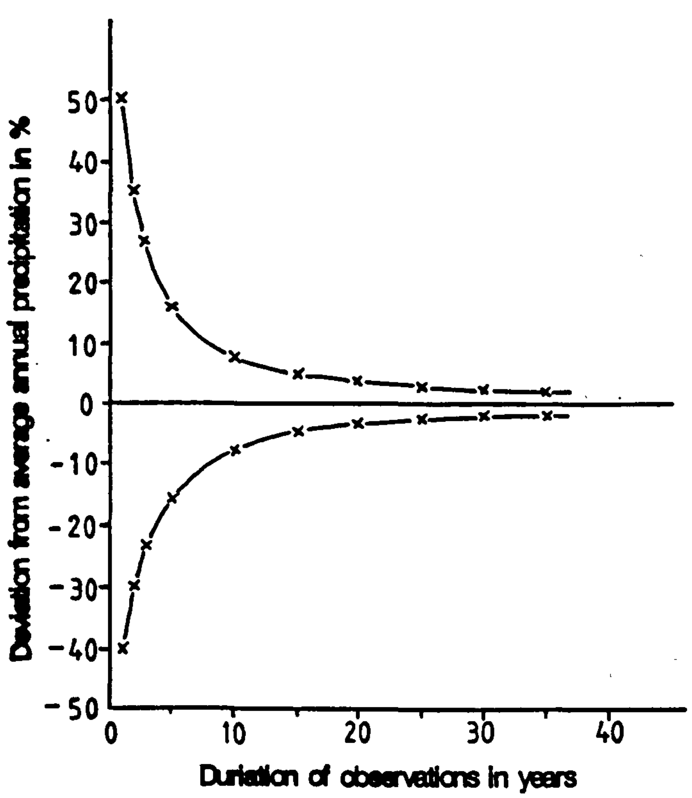

Fig 7.1 Deviations of the mean annual precipitation (calculated for a period of years) from the true long-term precipitation (after Binnie, in Wisler and Brater, 1959).

Two sets of mean annual rainfall values were calculated for each station, covering the periods 1962-84 (22 years) and 1962-77 (15 years) of their operation. Mean values were not calculated for five of the stations for the period 1962-84 because they had stopped operating in 1977 (Table 7.1).

According to Binnie's findings, the deviation of the estimated mean annual rainfall values from the true long-term rainfall should be approximately 3% and 5% for the periods 1962-84 and 1962-77 respectively.

As can be seen from Table 7.1, during the period 1962-77, the mean rainfall values are, on average, approximately 6% lower than the mean rainfall values corresponding to the period 1962-84. This is due to higher rainfall recorded during the last five years of the study period (Appendix Ic) as can be seen from the plots of the selected Arachamites, Neochori and Karytena stations which were chosen from those stations presenting unbroken records (see Fig 7.6 for position of the stations) and also from the plot of the Alfios river basin as a whole (Fig 7.2).

Secondly, the mean annual rainfall must be related to the topography by estimating the effect of the latter upon the former. When the calculated mean annual rainfall was plotted against the elevation of the respective stations, the elevation factor was found not to be very significant for the study area, despite the fact that it is considered by many investigators to be the most influential factor affecting the level of precipitation of a given area and is, therefore, the only factor taken into consideration in many studies. The plotted points representing the mean annual precipitation at the various stations against their elevation deviate greatly, rather than forming a straight line (Fig 7.3). If the only factor affecting the mean annual precipitation at a station were its elevation, the plotted points should run in a straight line.

Name of the station	Geographical position Longitude	Latitude	Elevation in m	Mean annual precipitation in mm 1962-84	1962-77	Station type, instruments
1 Akoros	22°10' E	37°11' N	800	1700	1454	P:Pg,Sg
2 Arachamites	22°14' E	37°27' N	760	1170	1108	P:Pg
3 Vytina	22°11' E	37°40' N	1010	1099	1066	M
4 Ekklisoula	22°10' E	37°27' N	630	1298	1211	P:Pg
5 Zoni	22°07' E	37°28' N	510	974	928	P:Pg
6 Karytena	22°02' E	37°20' N	490	986	972	P:Pg
7 Manaris	22°20' E	37°24' N	750	996	963	P:Pg
8 Megalopolis	22°08' E	37°23' N	420	886	863	M
9 Neochori	22°05' E	37°21' N	500	1233	1160	P:Pg
10 Paparis	22°16' E	37°22' N	760	1333	1154	P:Pg
11 Potamia	22°08' E	37°18' N	390	1067	1018	P:Pg,Sg
12 Silimna	22°20' E	37°31' N	900	1130	1068	P:Pg
13 Souli	22°03' E	37°17' N	500	1118	1097	P:Pg,Pg-r,SPg
14 Chranoi	22°02' E	37°19' N	650	1220	1170	P:Pg
15 Karatoulas	22°11' E	37°28' N	800	-	1030	P:Pg
16 Kardaras	22°18' E	37°37' N	950	-	1323	P:Pg,Sg
17 Mallota	22°11' E	37°24' N	660	-	1205	P:Pg
18 Roino	22°17' E	37°35' N	1080	-	1061	P:Pg, Sg
19 Tsepelakos	22°16' E	37°32' N	1000	-	1174	P:Pg

Key: P: Precipitation stations, Pg: Raingauge, Pg-r: Raingauge recorder, Sg: Snowgauge, SPg: Rain/Snowgauge, M: Complete meteorological stations.

Station	Observation period	Mean annual precipitation in mm	Station	Observation period	Mean annual precipitation in mm
Vytina	1958-61	982	Chranoi	1945-60	1163
Megalopolis	1953-62	964	Souli	1945-60	1051

Table 7.1 Precipitation stations situated within and around the Alfios river drainage area (for positions see Fig 7.6).

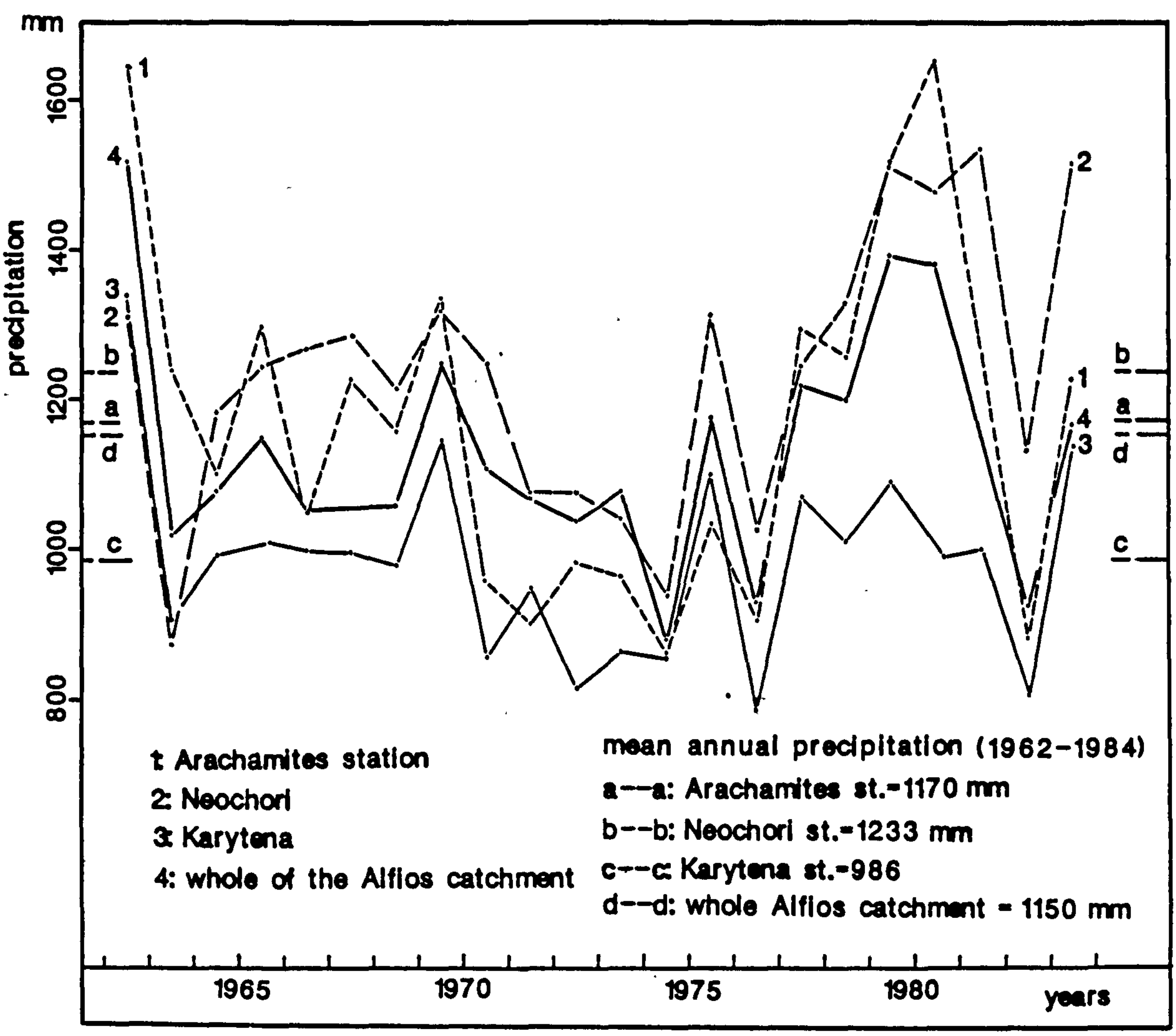

Fig 7.2 Annual precipitation recorded at the Arachamites, Neochori and Karytena stations and that calculated for the Alfios river basin as a whole.

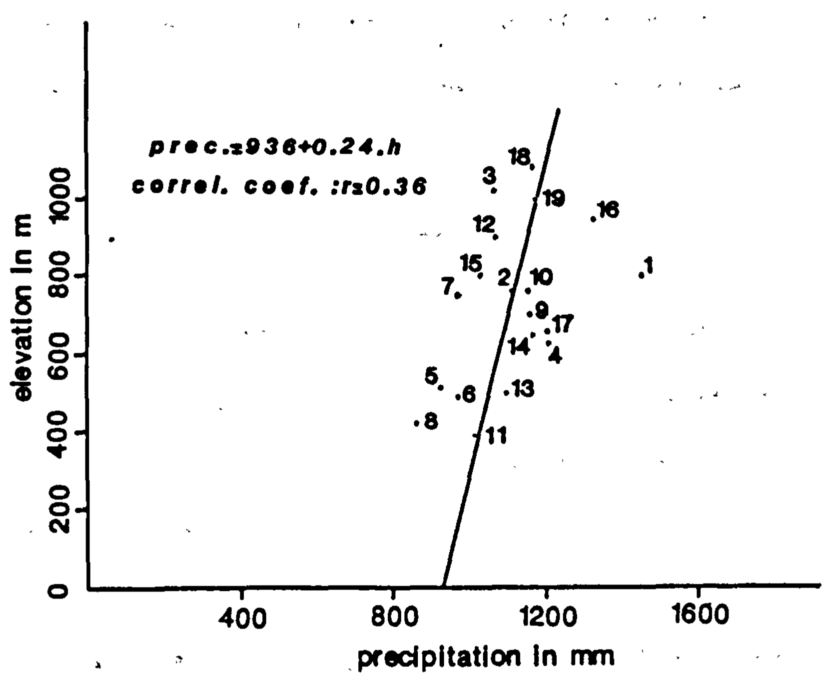

Fig 7.3 Relationship between mean annual precipitation and elevation.

The relationship between mean annual precipitation and elevation is linear and is represented by the equation $y = b + ax$ (1), where y = mean annual precipitation, x = elevation, b = the mean annual precipitation at sea level and a = the rate of increase.

To determine the line running closest to the plotted points as a whole, the method of 'least squares' was employed. According to this method, the a and b parameter-values are given by the formulae:

$$a = \frac{n\Sigma xiyi - (\Sigma xi)(\Sigma yi)}{n\Sigma i^2 - (\Sigma xi)^2} \quad (2) \qquad \text{and} \quad b = \bar{y} - a\bar{x} \quad (3)$$

where yi represents the mean annual precipitation at each station, xi the corresponding elevation, $\bar{y}$ the arithmetic mean annual precipitation and $\bar{x}$ the arithmetic mean elevation. In applying these equations to the data given in Table 7.1, the values were found to be as follows: $\Sigma xiyi$ = 15,199,430, Σxi = 13,560, Σyi = 21,025 and Σxi^2 = 10,480,400, while $\bar{y}$ = 1,107 and x = 714 (Appendix Id). When these determined values were inserted into equations 2 and 3, b was found to be equal to 936 and a to equal 0.24. Equation 1 therefore attains the form $y = 936 + 0.24\,x$ (4).

In addition, the correlation co-efficient r (which is determined as the ratio of the standard deviations Sx and Sy (ie $r = \frac{Sx}{Sy}$)) for the linear equation (ie r shows the degree of coincidence of the plotted points in respect of the drawn line as a whole) was computed by the formula:

$$r = \frac{n\Sigma xiyi - (\Sigma xi)(\Sigma yi)}{\sqrt{n\Sigma xi^2 - (\Sigma xi)^2} - \sqrt{n\Sigma yi^2 - (\Sigma yi)^2}} \quad (5)$$

By substituting in equation 5 the values referred to above, plus the given value Σyi^2 = 23,616,587 the correlation co-efficient, r, comes to equal 0.36. The very low degree of correlation (r = 0.36 or 36%) between the mean annual precipitation and the elevation indicates that other topographical factors strongly affect the precipitation in this area and thus there is a need to consider the effect of these other factors.

Spreen (1947) described a graphical correlation technique for relating the mean annual precipitation to topographic parameters, namely elevation, maximum slope of land, exposure and orientation. The technique can be used to estimate the effect of topography upon precipitation and allows the investigator to adopt a rational approach to the areal distribution of precipitation.

The parameters introduced by Spreen are as follows:

1) Elevation of the station.
2) Slope: the maximum range in elevation within a five mile radius of the station (taken in this study as 10 km).
3) Exposure: the sum of those sectors of a 20 mile radius circle (taken here as 35 km) centered at the station and not containing a barrier 1,000 feet (taken here as 300 m) or more above the elevation of the station (expressed in degrees of azimuth).
4) Orientation: the direction to the eight points of the compass of the greatest exposure, as defined above. In cases of equal exposure in two directions, the orientation is taken as that of the exposure which opens downstream, ie towards the lower elevation.

The precipitation value at a station is also influenced by other physiographical factors such as its distance from the coast or in general from a source of moisture or a mountain range, as referred to by Linsley et al. (1949), although these factors have not been considered during this study.

A brief description of the mechanisms of the successive introduction of the five variables (ie precipitation, elevation, slope, exposure and orientation) according to the Spreen method, is given below. This method is based on obtaining values of precipitation graphically as a function of elevation for various values of slope. Subsequently, by relating these

Name of the station	Topographic parameters				Mean annual precipitation (mm)	Estimated precipitation (mm)	Error
	Elevation (m)	Slope (m)	Orientation	Exposure (°)			
1 Akoros	800	810	NW	195	1454	1380	74
2 Arachamites	760	510	SW	150	1108	1140	-32
3 Vytina	1010	970	NW	60	1066	1170	-104
4 Ekklisoula	630	610	SW	85	1211	1050	161
5 Zoni	510	910	NW	75	928	850	78
6 Karytena	490	1050	NW	110	972	890	82
7 Manaris	750	500	SW	140	963	1140	-177
8 Megalopolis	420	680	SW	50	863	880	-17
9 Neochori	500	790	SW	110	1160	1120	40
10 Paparis	760	490	SW	140	1154	1160	-6
11 Potamia	390	910	0	0	1018	960	58
12 Silimna	900	950	SW	150	1068	1185	-117
13 Souli	500	790	SW	130	1097	1130	-33
14 Chranoi	650	740	SW	120	1170	1130	40
15 Karatoulas	800	620	SE	200	1030	1110	-80
16 Kardaras	950	1030	SE	20	1323	1270	53
17 Mallota	660	590	SW	110	1205	1070	135
18 Roino	1080	900	S	95	1061	1265	-204
19 Tsepelakos	1000	850	S	195	1174	1140	34

Note: a - Zero degrees for exposure and zero degrees for orientation indicate stations completely enclosed by a barrier within the 35 km radius.

b - The topographic parameters apart from elevation were obtained from the topographic map, scale 1:200,000.

Table 7.2 Topographic parameters of the precipitation stations used in the application of Spreen's method and mean annual precipitation measured and calculated for the period 1962-77.

values to orientation and thence to exposure, a set of working graphs is obtained. A high degree of correlation is shown to exist - tested by drawing a further graph - between the observed values of precipitation and those estimated from the graphs (Fig 7.4, a to d).

The Spreen method is described in more detail below:

Initially, precipitation is plotted against elevation and the points are labelled with the relevant values of slope. Thus, by sketching a first approximation of a family of curves for selected values of slope, a relationship is demonstrated between these three variables (precipitation, elevation and slope) (Fig 7.4a).

Next, a vertical axis is drawn below the three variable graphs and graduations are marked on it for plotting actual precipitation, while the axis common to both charts now represents the values of precipitation computed from the first family of curves. Then, the computed precipitation values are plotted against actual precipitation values on the second chart and the points are labelled with the corresponding values of the fourth variable, orientation. Here, too, a first approximation of a family of orientation curves is drawn (Fig 7.4b).

The fifth variable, exposure, is introduced in a similar manner. The actual precipitation values - horizontal axis of the third graph - are plotted against those computed from the correlation of the first four variables. The precipitation values are obtained by following the horizontal of the appropriate elevation, as represented in graph 7.4a, until it meets the curve of the given slope. At this point, the line is projected downwards into graph 7.4b until it meets the corresponding orientation curve. A reading taken at this point represents the computed value of precipitation. The points are labelled with the corresponding exposure value and curves representing selected ranges of exposure are then drawn (7.4c).

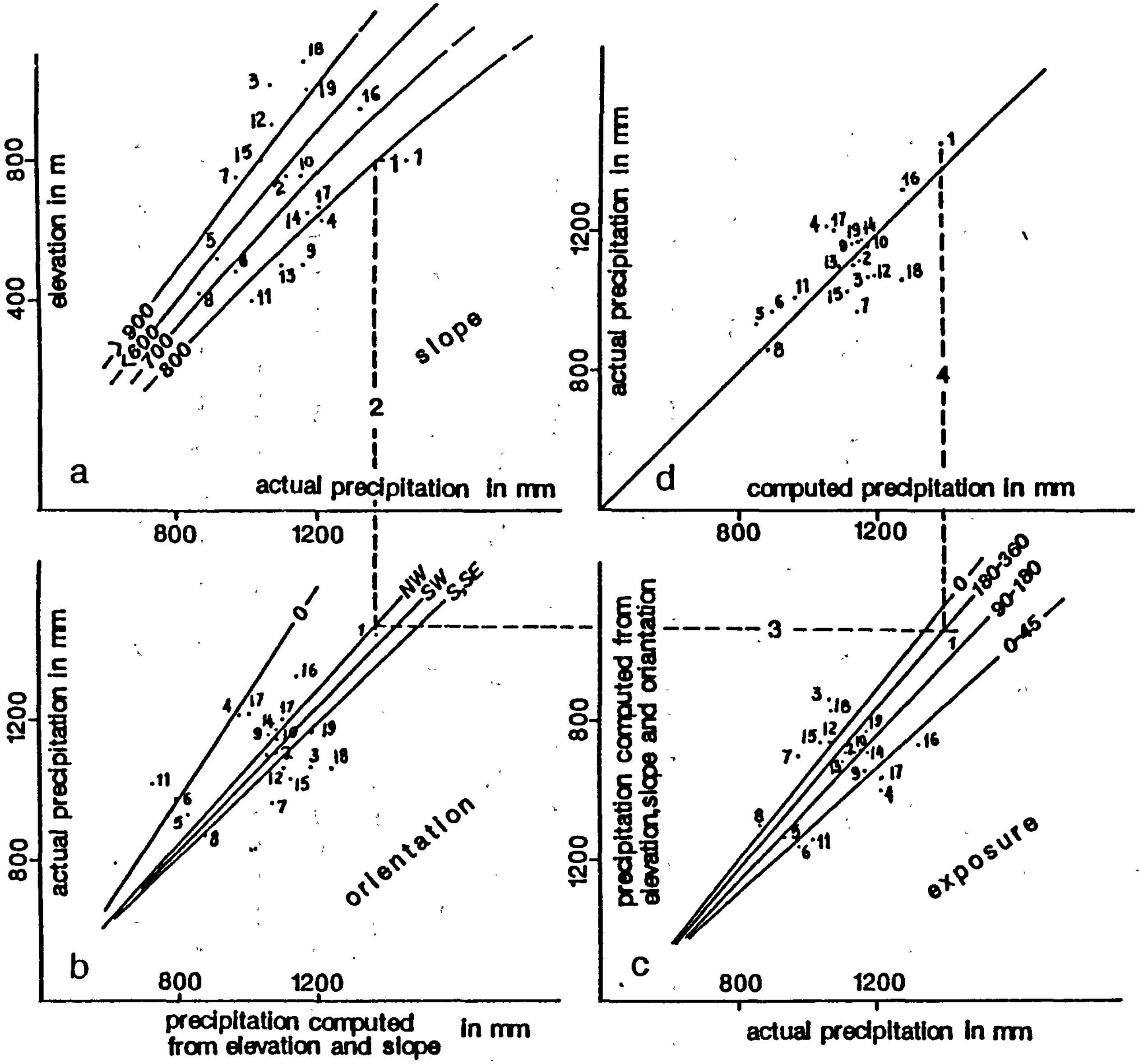

Fig 7.4 Application of Spreen's method
For exaplanation see text.

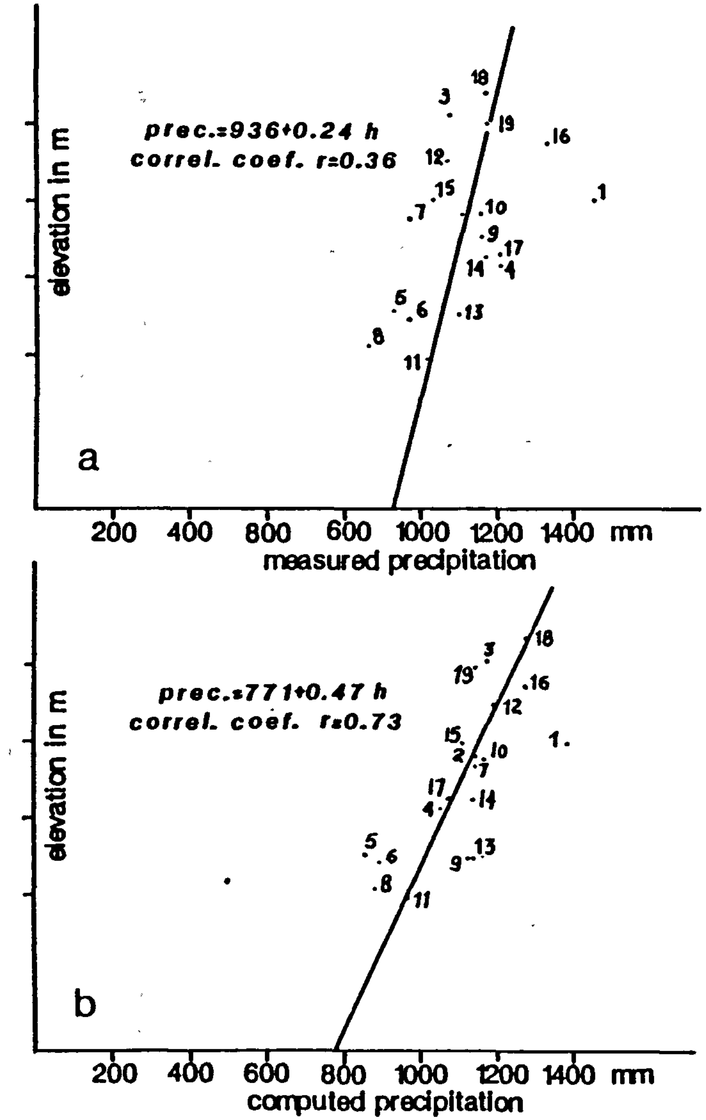

Fig 7.5 Correlation between:
a) elevation and measured precipitation
b) elevation and computed precipitation

Since all the sets of curves obtained by the above procedure are first approximations, further refinements are necessary. These are obtained by repeating the same procedure or by proceeding through the graphs in the reverse order from that in which they were derived.

Finally, it is necessary to test the graphically derived precipitation values by plotting the actual mean precipitation values for each station against those obtained by proceeding through the adjusted graphs (in the manner shown by steps 1 to 4 indicated by the dotted line on Fig 7.4) (Fig 7.4d). A high degree of correlation is shown to exist between the observed values of precipitation and those estimated from the graphs. The degree of scatter about the line of perfect correlation is shown on this graph.

The values of the mean annual precipitation for each station computed according to Spreen's method as described above and represented graphically in Fig 7.4 (steps a through to c) and tested (7.4d) are listed in Table 7.2. These mean annual precipitation values are plotted against elevation (Fig 7.5b) in order to obtain a correlation between elevation and precipitation.

A new line closer to the plotted points is drawn according to the equation $y = 771 + 0.47\ x$ (6). This was derived from equations 2 and 3 by replacing into them the newly evaluated data: $\Sigma xiyi = 15{,}396{,}700$, $\Sigma xi = 13{,}560$, $\Sigma yi = 21{,}040$, $\Sigma xi^2 = 10{,}480{,}400$, while $y = 1{,}107$ and $x = 714$ (see Appendix Id), from which it results that $a = 771$ and $b = 0.47$.

The correlation coefficient, r, for the new variables (elevation and computed mean annual precipitation) is found to be 0.73 (or 73%) by using formula 5 and substituting the evaluated data given above plus $\Sigma yi^2 = 23\ 633\ 350$. This high value of correlation coefficient indicates that there is a higher degree of correlation between the two variables elevation and

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Fig 7.5 Isohyetal map of the Alfios river catchment (1962-77).

mean annual precipitation after the latter is adjusted. In practice, the actual influence of the other topographic parameters, except elevation, on the precipitation value thus calculated was eliminated.

Finally, the isohyetal map (Fig 7.6) for the period 1962-77, showing the distribution of precipitation over the catchment area of the Alfios river, was constructed. This was based on equation 6, which determines the ratio of increase of precipitation in respect of elevation. The actual precipitation measured at each station was also taken into consideration.

7.2.2 Monthly rainfall

The following Table (7.3) gives the mean monthly values of precipitation over the wider area of the Megalopolis basin (Alfios catchment area) for the period 1962-77, calculated from the data from the nineteen stations named in Table 7.1 (see Appendices Ia and Ib).

Month	Mean precipitation (mm)	Percentage of the total	Month	Mean precipitation (mm)	Percentage of the total
October	99.8	9.0	April	67.2	6.1
November	137.4	12.4	May	46.1	4.2
December	222.4	20.1	June	34.5	3.1
January	154.7	14.0	July	27.3	2.5
February	155.4	14.0	August	19.3	1.7
March	103.5	9.4	September	39.1	3.5

Table 7.3 Mean monthly precipitation over the Alfios river catchment during the period 1962-77 (mean annual precipitation = 1,107 mm).

From Table 7.3 and also from the histogram (Fig 7.7), it can be seen that precipitation occurs predominantly during the wet season from October to March (145 mm), while during the dry season (April to

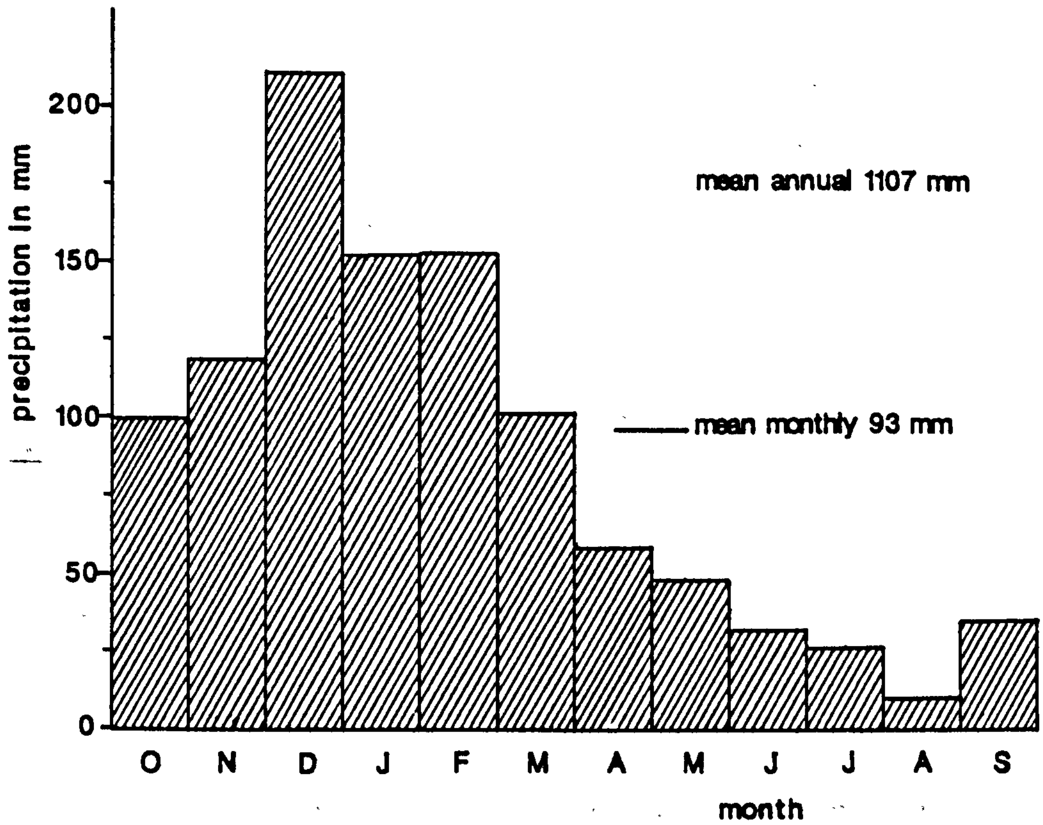

Fig 7.7 Histogram of the mean monthly precipitation over the Alfios river catchment (1962-77).

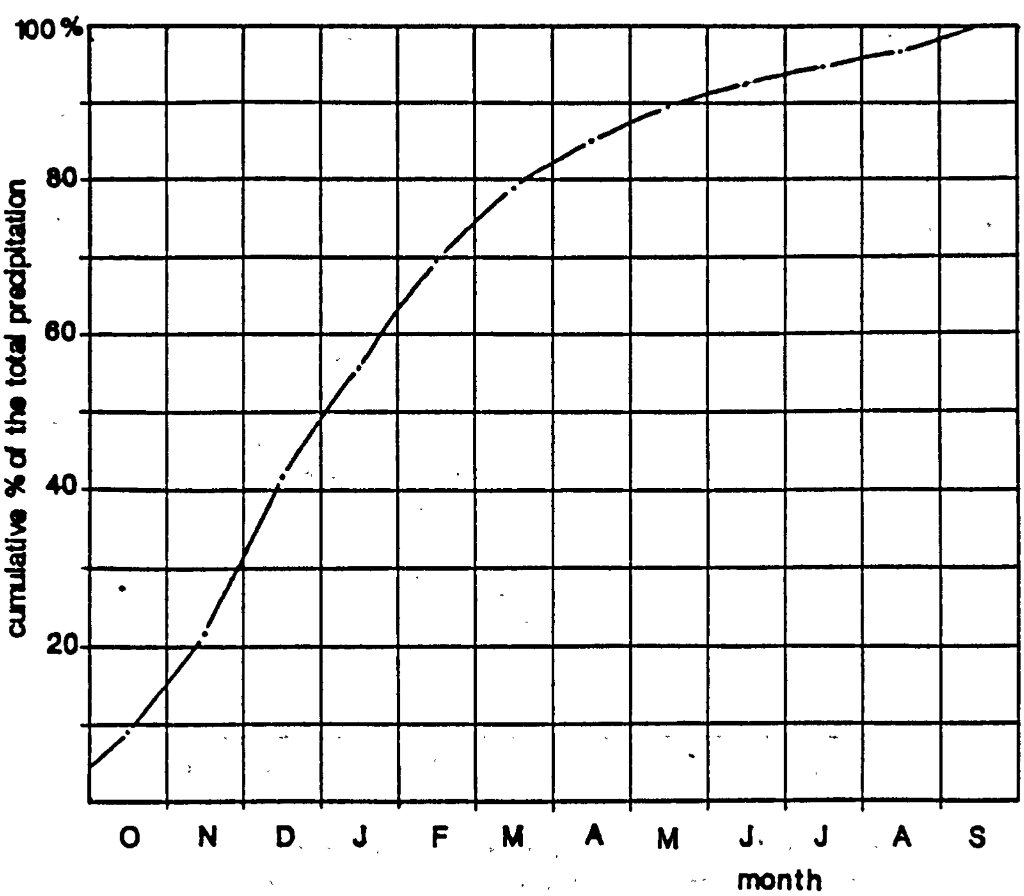

Fig 7.8 Cumulative percentage of the total precipitation over the Alfios river catchment (1962-77).

September) only 38 mm of rain falls, bringing the mean monthly value for the year to 93 mm (mean annual total = 1,107 mm). The wettest month is December, followed by January, while August, followed by July, is the driest month. A general observation can be made that the summer months (June, July and August) exhibit a higher precipitation (average 79 mm) around Megalopolis than seen in other areas of the Greek mainland which experience long, completely dry summers.

From Figure 7.8 it can be seen that approximately 78% of the rain falls from October to March inclusive and the remaining 22% from April to September. Figure 7.9 gives the mean monthly precipitation at the Megalopolis station for the period 1962-83 and also the mean number of rain days for each month for the same period. A good correlation between these two parameters is observed.

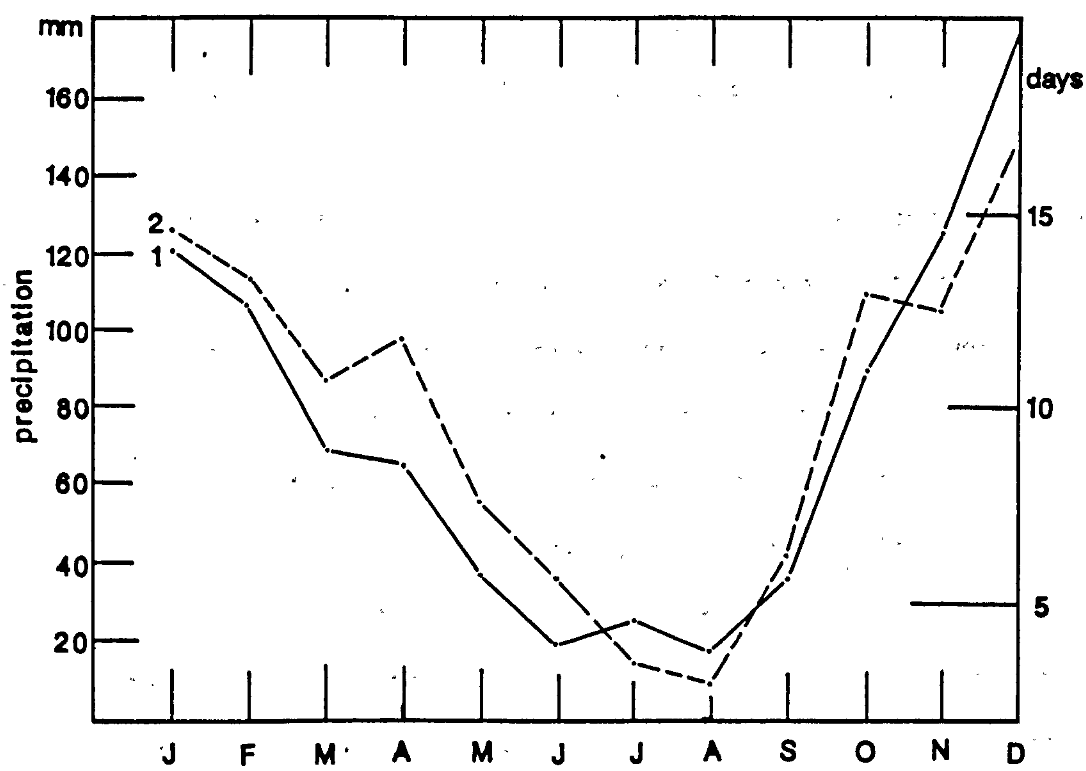

Fig 7.9 Mean number of rain days per month (1) and mean monthly precipitation (2) at the Megalopolis station for the period 1962-83 (after Kyriakopoulos 1984).

7.3 Evapotranspiration

Evapotranspiration is the sum of the total amount of water evaporating from the soil and that transpiring from plants. Several factors affect actual evaporation:

1) Atmospheric, such as degree of humidity, air temperature, wind velocity and, to a certain extent, atmospheric pressure.
2) Hydrogeological, such as the moisture state of the soil, the water table depth, the porosity and the lithology of outcrops.
3) Geographical, such as elevation and solar radiation, while factors such as the kind of vegetation, its density and depth of the roots, predominantly affect transpiration.

Actual evapotranspiration (E) is distinct from the potential evapotranspiration (Ep) which involves a supply of moisture, either from the soil or from the atmosphere, in the form of precipitation which is at all times sufficient to meet the highest demands of the transpiring vegetation cover (maximum hydrological evapotranspiration, Coutange 1956).

In practice, these demands are not always met and actual evapotranspiration can differ considerably from potential evapotranspiration, the actual rate generally being lower than the potential. It is agreed that transpiration is controlled by the soil moisture state and that it falls to zero when soil moisture is reduced to the wilting point. It is also generally accepted that transpiration runs at the potential rate when soil moisture is at, or above, field capacity. What occurs within the intermediate stages between soil moisture being at field capacity and at wilting point is not completely understood, although a good summary of the problems involved can be found in Ward (1974).

Various methods and formulae for approximating actual and potential evapotranspiration have been developed, none of which is generally suitable for all purposes (Linsley et al., 1975).

The potential evapotranspiration can be calculated by the formula developed by Thornthwaite (1948), $Ep = 1.6\left(10\,\frac{T}{I}\right)^a$ where Ep represents the monthly potential evapotranspiration and T the mean temperature during that month, while $a = 0.49239 + 10\ 1{,}792 \times 10^{-5}\ I - 771 \times 10^{-7} I^2 + 675 \times 10^{-9}\ I^3$, where I is the sum of the monthly indices of the potential evapotranspiration given by the formula $i = \left(\frac{T}{5}\right)^{1 \cdot 514}$.

A simplified approach developed by Turc (1954) is based on many hydrological data studies and permits the calculation of the actual evapotranspiration from the mean annual precipitation and temperature. It does not take into consideration the factor of vegetation, which considerably affects the rate of transpiration. It uses the formula:

$$E = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}}$$

where E equals the actual annual evapotranspiration in mm, P equals the mean annual precipitation in mm and L equals $300 + 25T + 0.005T^3$, where T is the mean annual temperature in °C.

Another simplified formula was developed by Coutange (1956). That is, $D = P - LP^2$, where D equals actual evapotranspiration in m, P is the mean annual precipitation in m and the factor $L = \frac{1}{0.8 + 0.14T}$, where T represents the mean annual temperature in °C.

Marinos (1975), in his evaluation of the data used in various hydrological studies (eg water balances of basins) carried out for various karstic areas of Greece by the investigators, stated that the calculation of evapotranspiration by the Turc or Coutange equations was applicable with good results only in such karstic areas where high mean annual rainfall and low temperature (ie $P>1200$ mm and $T<14$°C or $P>1500$ mm and $T<19$°C) conditions existed. Under other conditions, these methods could result in a high degree of error. He also stated that the Turc equation, being that generally used in Greece, gives better results when applied than does the Coutange equation (especially when Turc's developed formula is used, in which L is calculated by $T = \frac{\Sigma PiTi}{\Sigma Pi}$, where Pi and Ti represent the mean monthly values of precipitation and temperature respectively). Additionally, he reports that the application of the formulae gives better results when less than half of the basin is covered by carbonate rocks.

Both Turc's simplified formula and Coutange's formula were used to calculate the actual evapotranspiration for the Megalopolis and the Assea stations, for which temperature data are available (see Section 7.3.1). For the Megalopolis station (elevation 420 m), a mean annual precipitation of 886 mm for the period 1962-84 and a mean annual temperature of 14.3°C (1963-83) were computed. For the Assea station (elevation 660 m), the corresponding values are 965 mm and 12.9°C for the period 1973-84. By substituting these values in the above formulae, the following values for evapotranspiration at these stations were obtained:

Station	Precipitation in mm	Temperature in °C	Evapotranspiration					
			Turc	%	Coutange	%	Average	%
Megalopolis	863	14.3	609	71	606	70	608	70
Assea	965	12.9	593	61	607	63	600	62

Table 7.4 Evapotranspiration values calculated for the Megalopolis and Assea stations using the Turc and Coutange methods.

It is calculated that, in the area surrounding the Megalopolis station, evapotranspiration accounts for 70% of the total precipitation while, at the Assea station, it accounted for only 62% on average. These values are considered to be relatively high. Karkulias (1975) estimated, using data from the Megalopolis station, that, for the periods 1962/63 to 1970/71, evapotranspiration accounted for 54% of the total precipitation in the Megalopolis area.

7.3.1 Air Temperature

Air temperature records are available for the study area only from the Megalopolis Meteorological Station, located at the Power Station (elevation 420 m), for the period 1963-83 and from the Assea Station for the period 1973-84. Data for comparison are available from the Tripolis Meteorological Station.

Temperature in °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean minima	1.4	2.1	3.4	5.8	8.7	11.6	13.7	13.7	11.7	8.7	5.0	3.3	7.4
Mean maxima	10.5	11.2	14.6	17.4	23.3	28.1	30.5	30.4	27.2	21.4	15.8	12.3	20.2
Mean monthly	6.0	6.6	9.0	11.6	16.0	19.8	22.1	22.1	19.4	15.0	10.4	7.7	13.8

Table 7.5 Mean minimum, maximum and monthly temperatures recorded at the station of Megalopolis (1971-83).

The mean annual temperature at the Megalopolis station, for the period 1971-83, was 13.8°C, while the mean minimum was 7.4°C and the mean maximum 20.2°C.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean monthly T in °C	6.3	7.1	9.2	12.0	16.2	20.3	22.8	23.0	20.1	15.5	11.1	8.0	14.3

Table 7.6 Mean monthly temperatures recorded at the station of Megalopolis for the period 1963-83.

As can be seen from Table 7.6, the mean annual temperature calculated for the period 1963-83 and accounting for 14.3°C, is a little higher than the 13.8°C calculated for the period 1971-83 (Appendix Id).

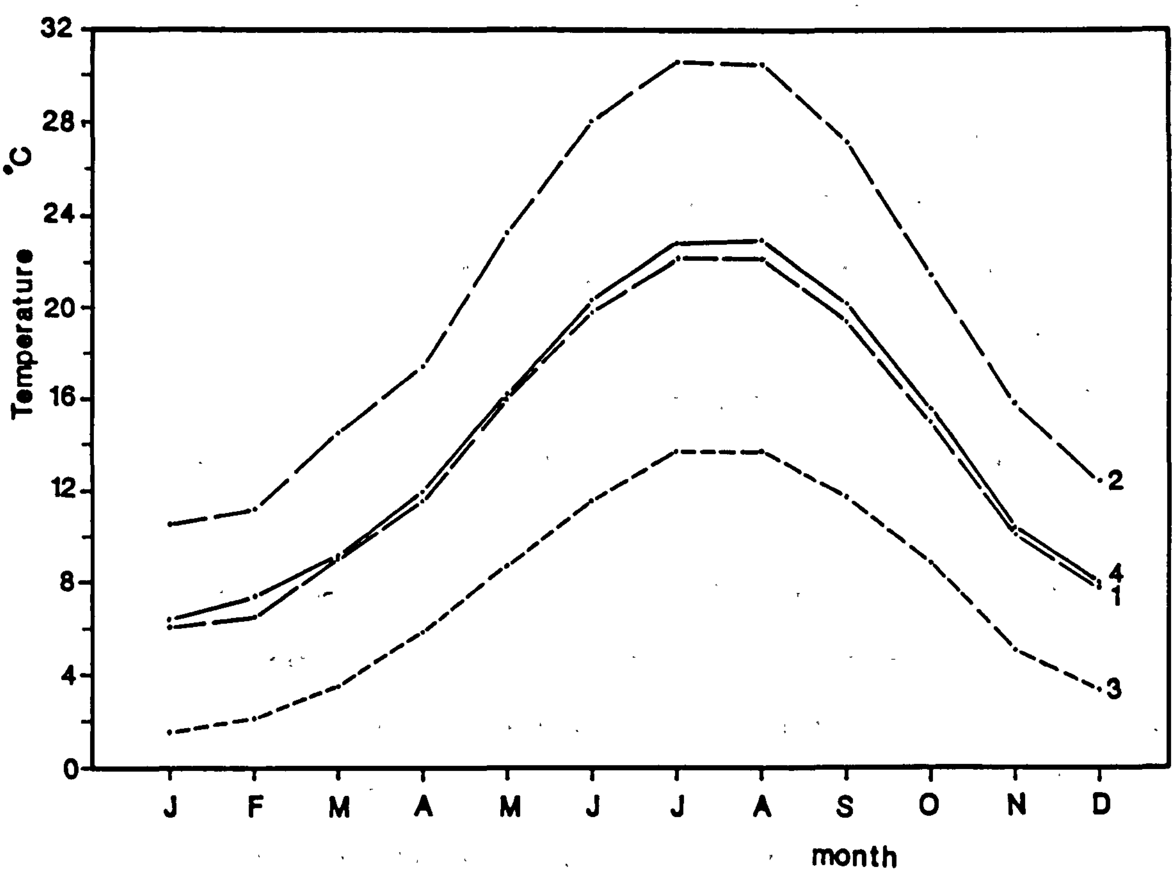

Fig 7.10 Temperatures measured at the Megalopolis station
1. Mean monthly (1971-83). 2. Mean monthly maxima (1971-83).
3. Mean monthly minima (1971-83). 4. Mean monthly (1963-83).

From Figure 7.10, it can be seen that the annual curves of the temperature rates show a simple fluctuation with maxima occurring during July and August and minima during January.

Temperature in °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Absolute maximum	21.5	22.5	24.5	29.0	35.0	39.5	43.0	38.0	35.5	33.0	25.0	19.5	43.0
Absolute minimum	-8.5	-8.0	-6.0	-2.0	2.0	6.0	7.0	8.0	4.0	-1.5	-5.5	-7.0	-8.5

Table 7.7 Absolute minimum and maximum temperatures (Megalopolis) (1971-83), after Kyriakopoulos (1984).

From Table 7.7, it can be seen that the hottest day occurred during July (43°C), while the coldest night was recorded in January (-8.5°C).

The number of days (nights) during which the temperature falls below 0°C average 35 per year, eleven of which are in January on average, while the days (nights) during which the temperature remains below 0°C for the total 24 hours are very rare (less than twenty in the last nineteen years) (Kryriakopoulos 1984).

The temperatures at the Assea station (elevation 660 m), situated in a basin approximately 15 km to the east of and some 240 m above the Megalopolis station, show a lower range of values during the year, with mean annual temperatures lower, on average, by 1.8°C (Table 7.8). Here, the coldest months are January and February, while the hottest month is July.

Temperature in °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean minima	-7.4	-8.0	-3.8	0.8	3.3	6.3	7.4	7.8	6.9	2.2	-2.0	-3.8	0.8
Mean maxima	14.6	14.9	19.3	22.7	28.7	31.3	34.0	31.4	29.0	25.3	20.6	15.5	23.9
Mean monthly	4.6	4.5	6.8	10.3	15.3	18.7	21.3	18.9	17.4	13.6	8.7	5.8	12.9

Table 7.8 Mean minimum, maximum and monthly temperatures recorded at the station of Assea (1973-84).

Due to the fact that data was only available from two stations, only a rough relationship could be established between elevation and temperature for the wider area of the basin of Megalopolis. According to this relationship, an average decrease of 0.3°C in the mean annual temperature for every 100 m increase in elevation was considered to occur in this area (Fig 7.11).

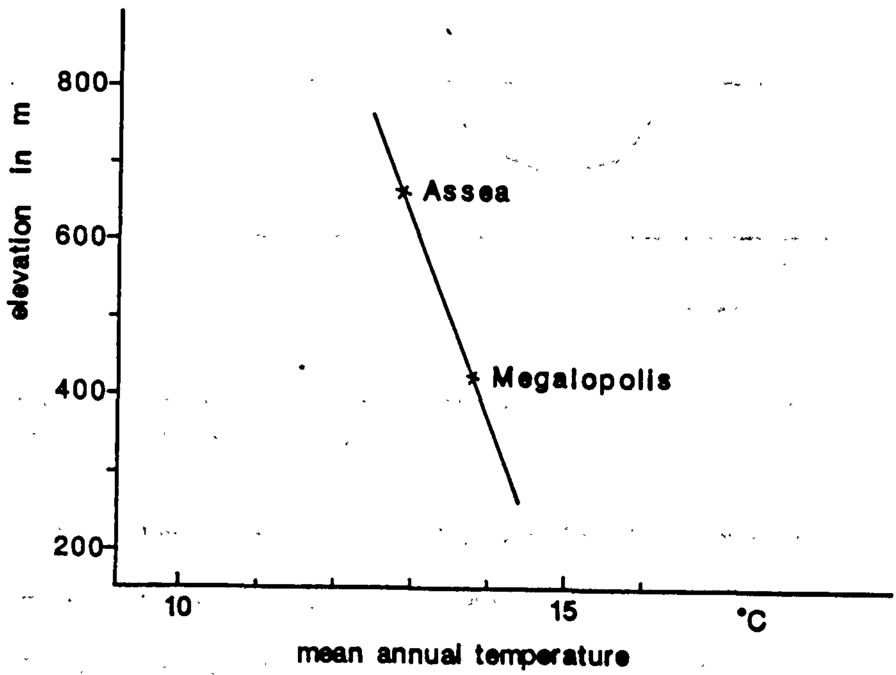

Fig 7.11 Relationship between elevation and mean annual temperature for the wider area of the Megalopolis basin.

7.3.2 Relative humidity

Data for the relative humidity are also only available from the Megalopolis station for the period 1971-83. From Table 7.9 and also from Figure 7.12, it can be seen that the relative humidity annual curve shows a simple fluctuation with its minimum occurring in July and its maximum during December, which is the rainiest month of the year, rather than during January, which is the coldest month.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
mean relative humidity %	78.6	76.7	71.9	68.9	63.4	56.0	54.0	55.1	63.2	72.0	77.8	80.0	68.1

Table 7.9 Mean monthly values of relative humidity (1971-83), after Kyriakopoulos (1984).

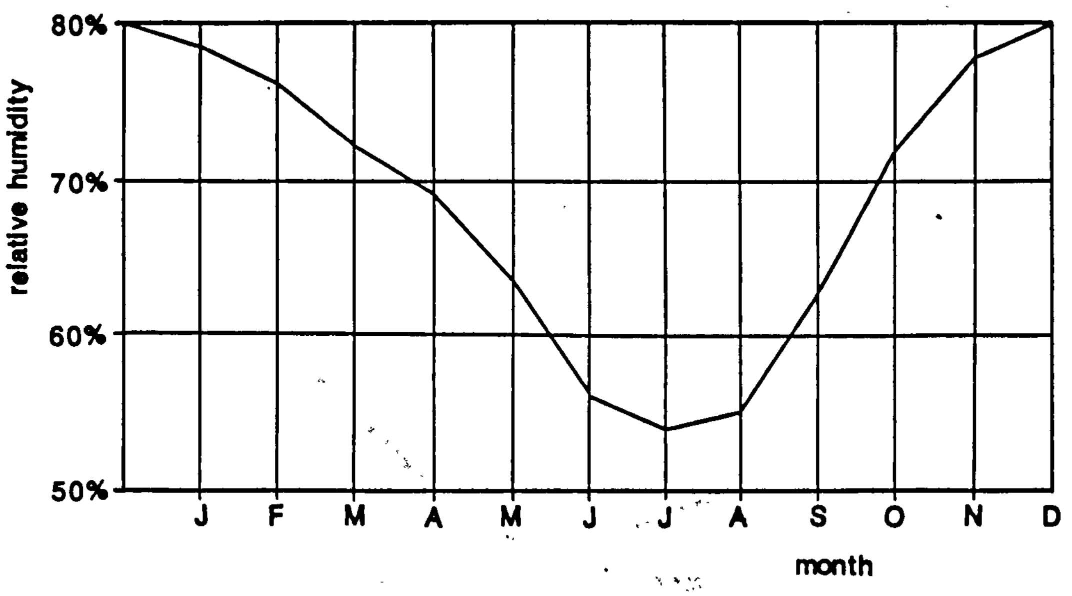

Fig 7.12 Mean monthly values of relative humidity (1971-83), after Kyriakopoulos (1984).

The relative humidity is much higher in the early morning (08.00 hours), ranging between 76% and 92% mean monthly values throughout the year, than during the afternoon (14.00 hours), when it ranges between 32% and 65% while, in the early night (20.00 hours), it exhibits medium values of between 51% and 85%. The difference between morning (higher) and afternoon (lower) relative humidity mean values is greater during summer than during winter.

7.3.3 Winds

Data on wind velocity and frequency in the study area are also provided by the Megalopolis station and cover the period 1972-83 (all the data have been evaluated by Kyriakopoulos, 1984). On a yearly basis, winds originating from north-westerly directions (NNW, NW, WNW) prevail, followed by winds from the easterly and south-easterly directions (ESE, SSE and S), while winds from the south-west and west are of the least importance (Fig 7.13). It can also be seen that wind speeds are generally moderate, with the north-westerly winds being the strongest. The percentage of periods of calm is quite high (24.5%), due in part to the morphology of the area.

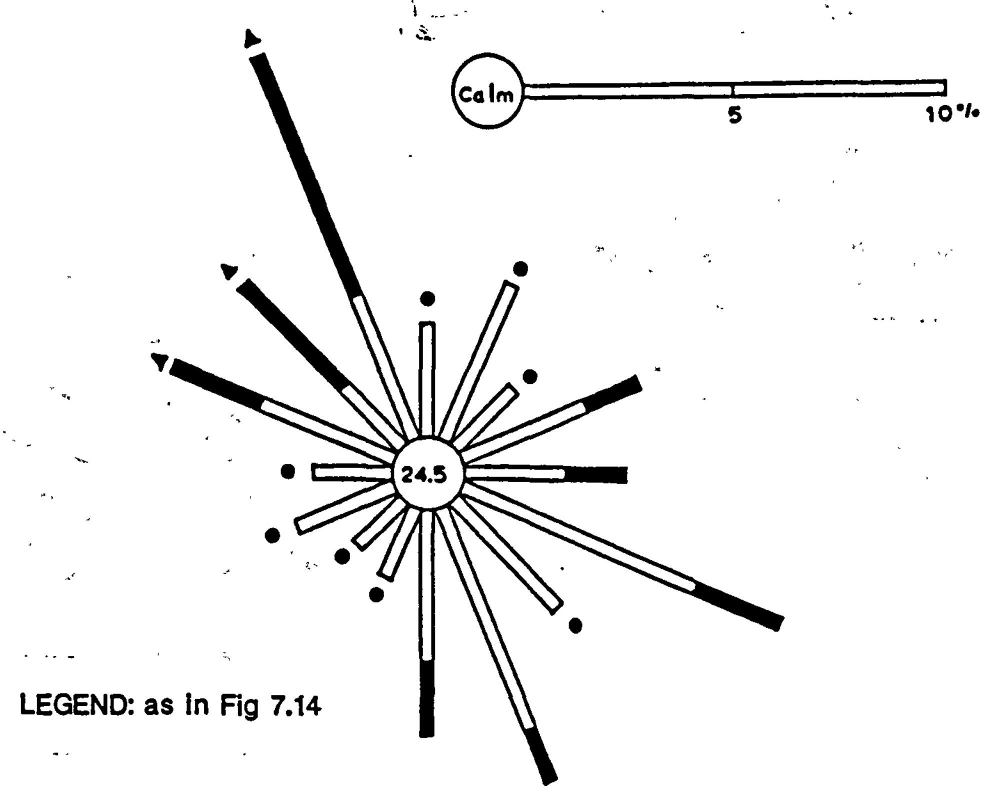

Fig 7.13 Mean annual wind direction-frequency and speed (1972-83) at the Megalopolis station, after Kyriakopoulos (1984).

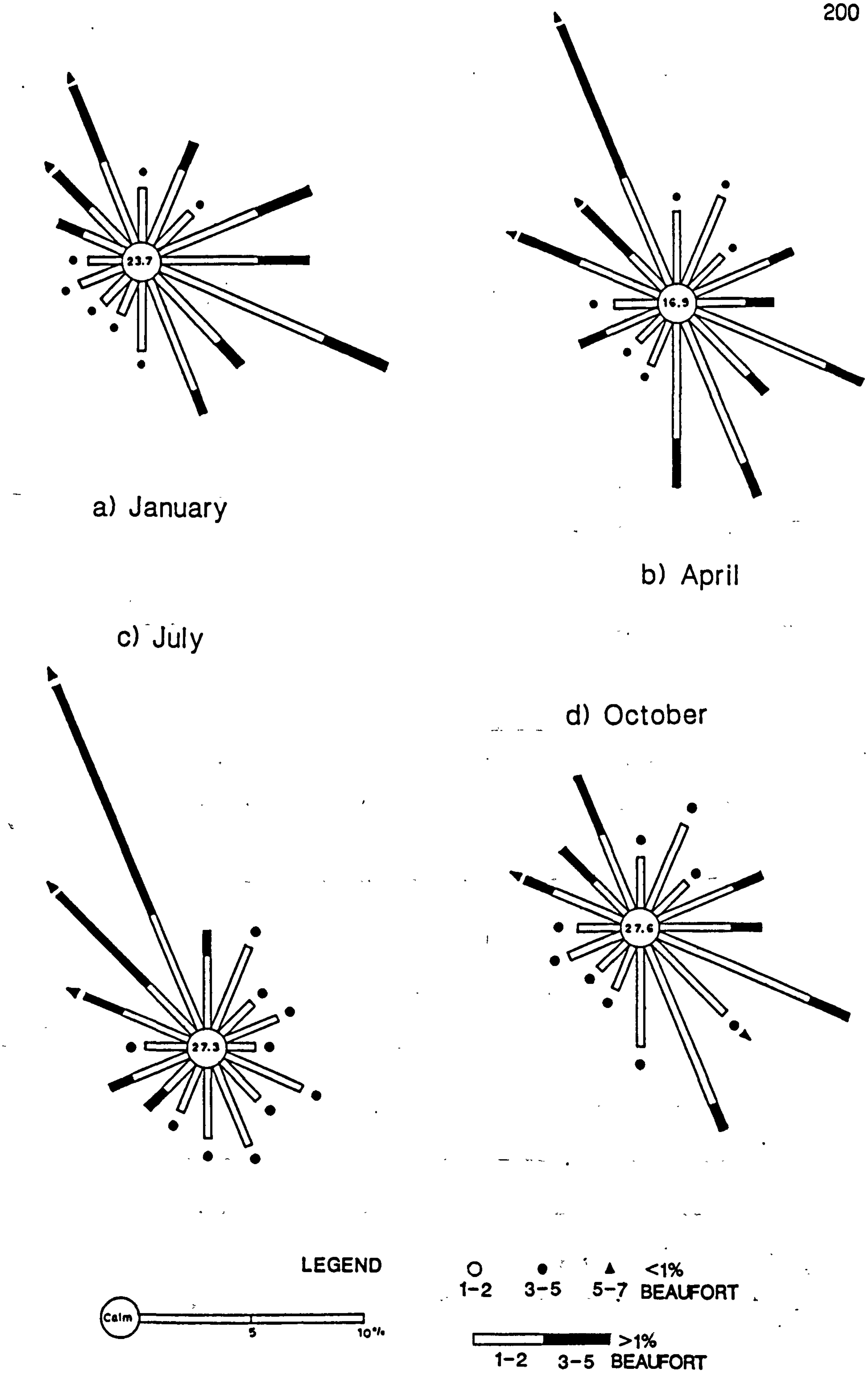

Fig 7.14 Wind directions and velocities at the Megalopolis station (1972-83), after Kyriakopoulos (1984).

From Figure 7.14(a-c) which shows mean wind direction-frequency and speed for the months January, April, July and October, taken as representative of the four seasons winter, spring, summer and autumn (similar charts can be obtained by plotting the mean values for each season), the following observations can be made:

1) During January, SE winds prevail in terms of direction-frequency, although the NNW winds are stronger.
2) During April, NNW and NW winds prevail in direction-frequency and speed but the SSE and SE winds are also quite frequent and strong.
During July, the NNW and NW winds dominate in direction-frequency and speed. The dry NNW winds which blow during the middle to end of summer are known as 'meltemia'.
During October, the SE winds are more frequent, although the NW winds are stronger.

Figure 7.15, which gives the mean annual wind speed independent of the direction, shows that, generally, very low values are recorded.

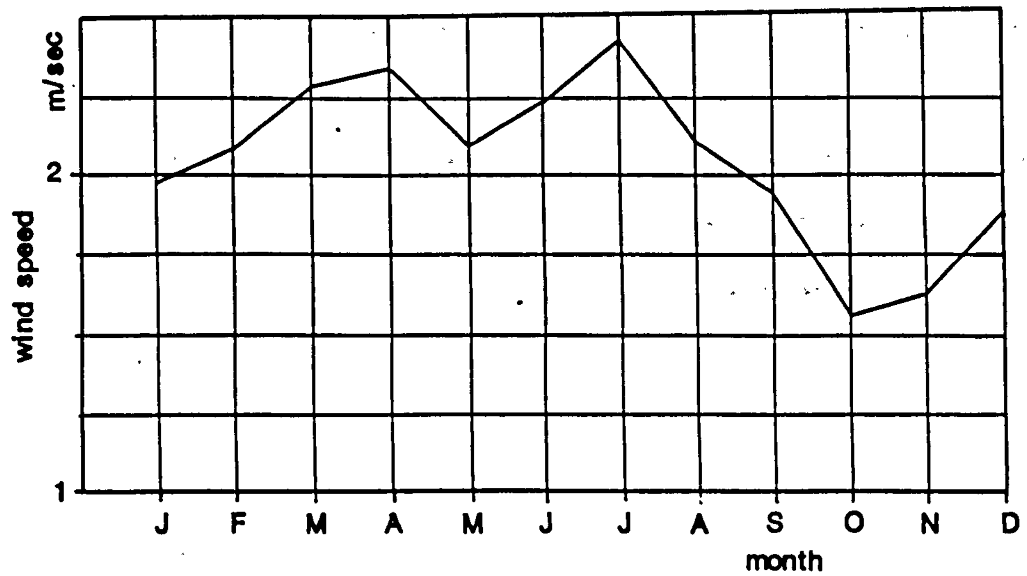

Fig 7.15 Mean daily wind speed at the Megalopolis station, after Kyriakopoulos (1984).

The mean daily values of the wind speed show a simple fluctuation with a maximum around 15.00 to 16.00 hours and a minimum between 06.00 and 08.00 hours. Variations are greater during the summer and smaller during winter.

7.4 Conclusions

Two sets of mean annual rainfall values were calculated for each of the 19 stations, covering the periods 1962-77 (15 years) and 1962-84 (22 years) of their operation. The arithmetic mean annual rainfall over the whole of the Alfios catchment was calculated at 1,107 mm for the period 1962-77 and 1,351 mm for the period 1962-84.

The precipitation equation, giving the mean annual rainfall in relation to the elevation, for the Alfios catchment, was calculated to be: precipitation = 936 + 0.24 x elevation. The low correlation (r = 0.36 or 56%) which was computed to exist between the elevation of the stations and the calculated mean annual rainfall, indicated the necessity of taking other topographic factors into consideration.

Spreen's (1947) graphical correlation technique was applied to relate precipitation to topographic parameters, namely elevation, maximum slope of land, exposure and orientation. By using this technique in the computation of the precipitation, the actual influence of the other topographic parameters, except elevation, on the precipitation values is, in practice, eliminated. The new precipitation equation (after the precipitation values had been adjusted) was found to be: precipitation = 771 + 0.47 x elevation. The correlation coefficient for this equation was computed to be: r = 0.73 or 73%.

The monthly rainfall varies greatly throughout the year. The mean monthly rainfall was 93 mm for the period 1962-77. The wettest month is

December (mean monthly rainfall 222.4 mm) followed by January (154.7 mm), while August (19.3 mm) is the driest month. Approximately 78% of the rain falls from October to March inclusive and the remaining 22% from April to September.

Evapotranspiration was calculated, by using both Turc's (1954) and Coutange's (1959) formulae, to account for 608 mm (or 70%) of the precipitation at the Megalopolis station, for the period 1963-83, and 600 mm (or 62%) for the Assea station, for the period 1973-84.

The mean annual temperature at the Megalopolis station (elevation 420 m) for the period 1971-83 was 13.8°C, while the mean minimum was 7.4°C and the mean maximum 20.2°C. The mean annual temperature at the same station, for the period 1963-83, was 14.3°C. At the Assea station (elevation 660 m) the mean annual temperature for the period 1973-84 was 12.9°C, while the mean minimum was 0.8°C and the mean maximum 23.9°C. An average decrease of 0.3°C in the mean annual temperature for every 100 m increase in elevation was calculated for the wider area of Megalopolis.

The relative humidity annual curve shows a simple fluctuation with its minimum occurring in July and its maximum during December. It ranges between 76% and 92% in the early morning, between 32% and 65% in the afternoon and between 51% and 85% in the early evening.

On a yearly basis, winds originating from north-westerly directions prevail, followed by those from easterly to south-easterly directions, although moderate wind speeds are generally recorded.

CHAPTER 8: CATCHMENT OF THE ALFIOS RIVER

8.1 Introduction - description of the Alfios catchment and drainage system

The wider area of the Megalopolis basin is drained by the Alfios and its tributaries of which the main ones are the Xerilas, Elisson, Lagadas, Sfikas, Kastritis and Valtos Choremiou (Fig 8.2).

The part of the drainage basin of the Alfios under study is located in the central-southern part of the Peloponnese and has a rhomboid shape, its sides striking in SSE-NNW and SW-NE directions (Fig 8.2). Much of it is mountainous, especially in the north, but the Megalopolis and Assea basins form low ground in the western and central-eastern areas. The Taygetos mountain (elevation 2,853 m - the highest in the Peloponnese) lies to the south, while the mountains of Trapezion (1,389 m) and Lykaeon (1,421 m) lie in the west and that of Maenalon (1,980 m) in the north-east. To the east, the basin is separated from the closed drainage basin of Tripolis (average elevation approximately 660 m) by a mountain range of low elevation (Fig 8.1).

The main part of the Alfios, actually consisting of an extension of the Xerilas tributary and running in a SSE-NNW direction through the Megalopolis basin, crosses its catchment asymmetrically, as it flows closer to its western watershed. The north-eastern part of the catchment, which makes up its greater part, is drained by the tributaries of the Alfios, the main ones being the Elisson and the Alfios stream, all running in a NE-SW direction, perpendicular to the predominant direction of drainage.

That part of the drainage network of the Alfios river upstream from the gorge of Karytena, the watershed of the main catchment and also those between the main tributaries, were drawn from the topographic maps (scale 1:50,000) issued by the Geographical Service of the Army. A detailed map on a scale of 1:75,000 of the drainage network of the Alfios river basin

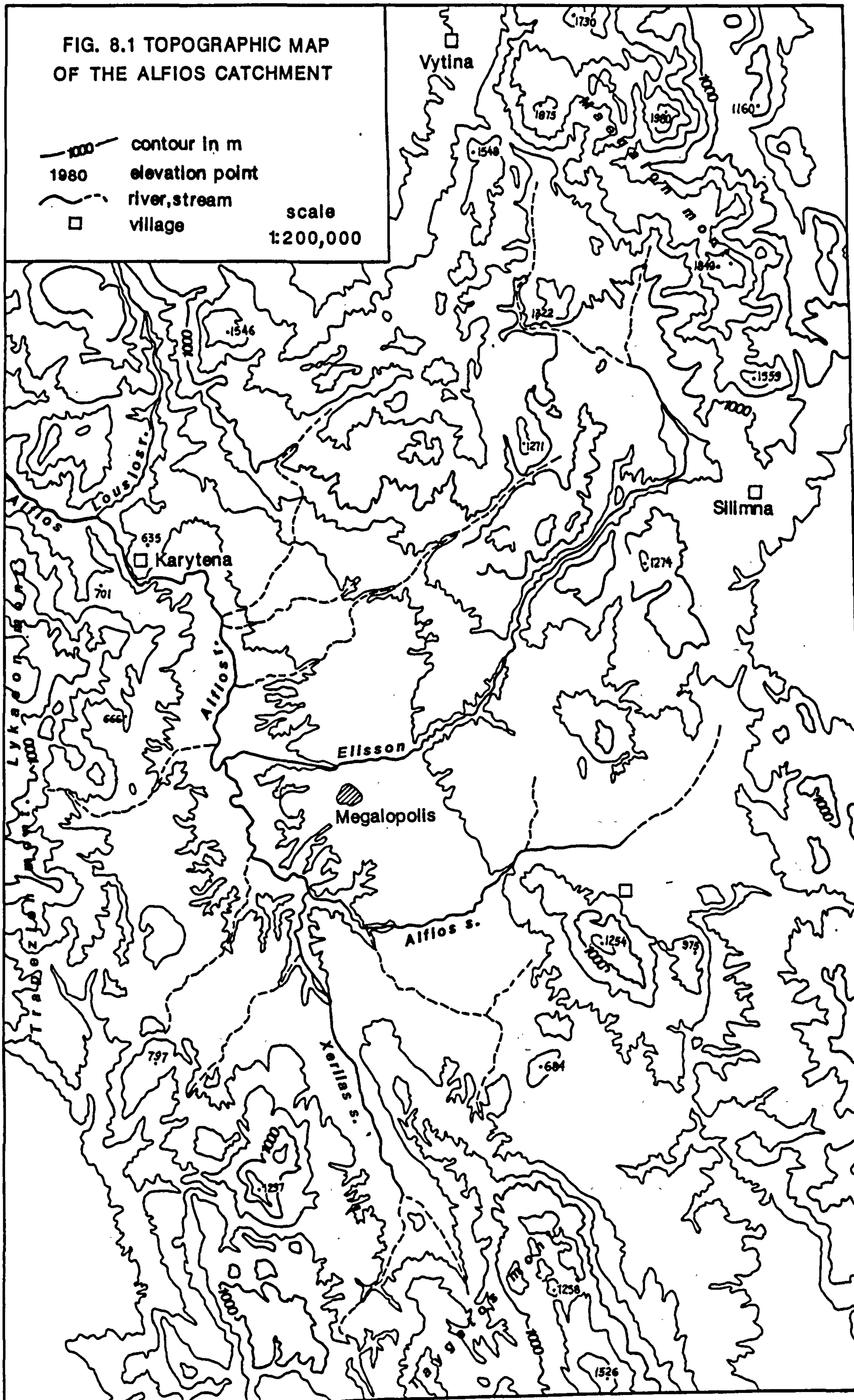

FIG. 8.1 TOPOGRAPHIC MAP OF THE ALFIOS CATCHMENT

is given in the pocket of Volume II. The same map, on a scale of 1:200,000, is also given in the text as Figure 8.2.

The various branches making up the drainage network were classified according to the Strahler method (1954a). According to this method, the smallest tributaries located in clearly defined valleys are designated Order 1. Where two first-order channels join together, a stream segment of Order 2 is formed. Where two of Order 2 join, a segment of Order 3 is formed and so forth. The trunk stream through which all the discharge of water and sediment passes is, therefore, the stream segment of the highest order. The order of a drainage basin is determined by the order of the main stream which drains it.

According to the above method of order designation, the Alfios river was assigned to Order 6. Its main tributaries were assigned to the following orders: Xerilas 5, Elisson 5, Alfios stream 5, Lagadas 5, Kastritis 4, Kutifarena 4, Lapatou 4, Valtos Choremiou 4, Zarzakis 4, Zaglakorema 4 and Sfikas 3.

A detailed quantitative analysis of the drainage system of the Alfios river basin was not undertaken, as it was considered to be beyond the purposes of the present study. Only the factors controlling the development of the drainage system and the patterns of its development are discussed in the subsequent sections.

8.1.1 Factors controlling the development of the catchment and the drainage system

The degree of development of the drainage system of a catchment is expressed by the following natural features:

a) density (d), being the total length of the various branches divided by the area they drain, and

b) frequency (f), being the total number of branches divided by the area.

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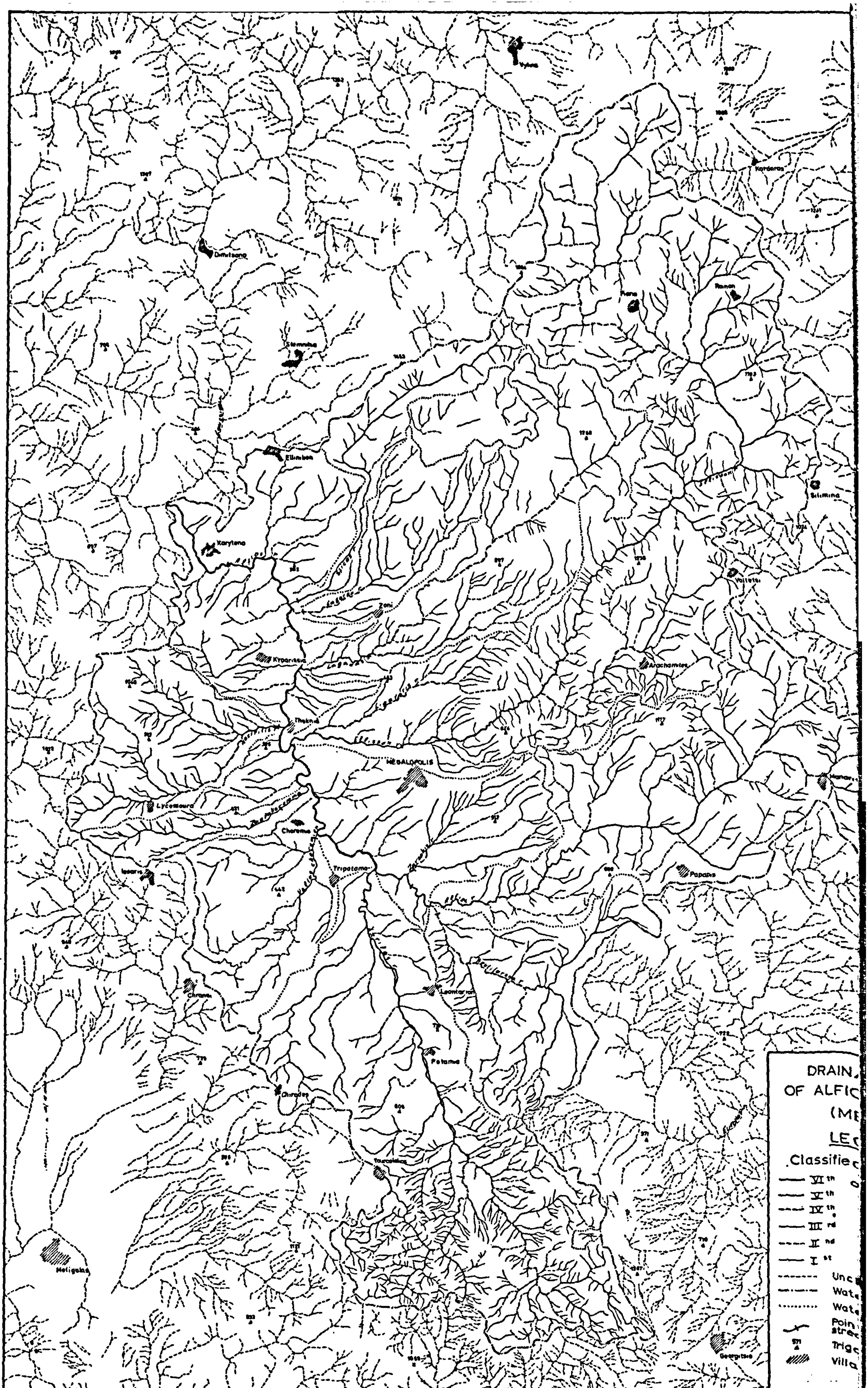
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The development and shape of the drainage system are controlled by a number of factors, such as the lithology and permeability of the bedrock, the tectonic deformation and structures present in the area, the relief and the precipitation, while resistance to erosion is also dependent on the factors referred to above, especially the lithology, tectonic deformation and also climate.

The geology of the catchment has a profound effect on the development of the drainage system. The lithology of the outcrops controls mainly the density but also the frequency of the drainage system. Sparse drainage systems with deep valleys are developed in highly permeable rocks, while the development of a dense drainage system with a great number of small branches indicates the presence of rocks of low permeability and high run-off.

The density of the various areas of the drainage system in the study area (ie of the Alfios catchment) is predominantly controlled by the lithology of those same areas*. The relief and the amount of precipitation have also affected its development.

Thus, a dense drainage system is developed on the impermeable flysch formation of the Tripolis zone and also over the impermeable metamorphic rocks of the Tripolis zone basement and the Phyllitic-Quartzitic series. This can be observed from just east of Megalopolis as far as the village of Arachamites, where the flysch and metamorphic rocks of the Phyllitic-Quartzitic series dominate.

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* Photogeological and geological maps of the area (scale 1:50,000) were used for the study of the effect of the lithology on the development of the drainage system over the wider area and for relating the latter to the former.

Despite the relatively high precipitation in the area (approximately 1,100 mm mean annual rainfall), a rather sparse drainage system has developed in the north-eastern part of the catchment of the Alfios river, from just east of Karytena up to the village of Arachamites, where the river runs over the carbonate rocks of the Tripolis zone and the limestones of the Pindic nappe. Where the river flows over the most permeable karstified carbonate rocks of the Tripolis zone, the drainage system is, in fact, less developed than where the river flows over the limestone of the Pindos zone.

To the west of the Megalopolis basin, where an alternation of outcrops of the first flysch and the Upper Cretaceous limestones of the Pindos zone occurs, a medium to low density drainage system has developed. Here, despite the presence of the impermeable first flysch, the low morphological relief appears to have been the most determinative factor in the development of the drainage system.

The most dense drainage system in the area is developed to the north of the Taygetos mountain where it forms part of the Xerilas tributary. The presence of the impermeable flysch of the Tripolis zone and the metamorphic rocks (basement of the Tripolis zone) from which this area is mostly built up, the high precipitation (1,670 mm mean annual rainfall for the period 1962-84) and the high relief of the area are all responsible for the dense nature of the development of the drainage system.

Finally, in the tectonic basins of Megalopolis and Assea, which are filled with unconsolidated clastic sediments, a sparse drainage system has developed, despite the general low permeability of the rocks filling these basins. The development of the drainage system here has been determined predominantly by the flatness of the morphology.

In addition to the lithological build-up of the catchment, tectonic deformation and structures such as folds, cleavages, joints and faults also control the degree of development of the drainage system, especially in the macro-permeable rocks.

It is noticed here that the morphological subsidences, the basins of Megalopolis and Assea, formed during the Lower to Middle Pliocene, were determined by faulting and a few of the faults can still be observed at the margins of these basins. The main direction of their development is SSE-NNW. Both were closed basins for a certain period up to the Middle Pleistocene, when they were filled with sediments of limnic and fluvial origin.

Faulting is particularly important in determining the shape of the system and was also significant for the determination of the directions of development of the Alfios catchment watersheds. The main branches and watersheds run in SSE-NNW and SW-NE directions, which are also the principal directions of faulting determined for the study area (see rose diagram of Fig 4.11).

The watersheds of the Alfios tributaries appear to have been similarly affected by the basic faulting lines. To the west of the Alfios river, the arrangement of the watersheds does not show a distinct pattern, while to the north and east, on the other hand, a number of oblong, elongated catchments are developed with their watersheds arranged predominantly in a SW-NE direction, although other directions can also be observed, coinciding with the determined secondary faulting directions.

The Xerilas tributary, one of the major tributaries of the Alfios river, runs in the same direction as the main branch of the Alfios river (ie SSE-NNW) and drains a trapezoidal catchment. The water divides of this catchment, except on its northern side, are developed in the same directions as that of the Alfios river. The Kutifarena tributary, together with the Alfios stream, the latter running in a S-SW direction, drains an area almost oblong in shape. The Elisson stream, another major tributary of the Alfios river, runs first in a SW direction, then turns SE and, finally, returns to a SW direction. It drains a catchment which can be divided into two oblongs, perpendicular to each other. Finally, the other three major tributaries of the Alfios river, the Lagadas, the Lapatou and the Sfikas, flow in a SW direction and join the main drainage direction almost at a right angle. Together, they drain an area almost oblong in shape.

Finally, it can be observed that over the whole catchment area of the Alfios river there is a characteristic pattern of straight lines and stripes arranged along certain directions, crossing the catchment and sometimes extending beyond it. A range of watersheds or branches of the drainage system, or both in alternation, occurs along this pattern, indicating the presence of major faulting zones and principal faulting directions.

8.1.2 Patterns of development of the drainage system

An examination of the drainage patterns reveals that they are significantly controlled by both the structure and the geology of the bedrock on a local and also on a wider scale. Some drainage patterns are considered to owe their shape entirely to joints, thrust planes, cleavages, faults and the presence of strata weakened by erosion.

The particular types of development (Twidale, 1976) encountered in the drainage system of the Alfios (Fig 8.2), are briefly described below:

i) Dendritic drainage. This implies uniform resistance of local bedrock and minimal slope of land surface.

ii) Parallel drainage. This develops on long straight slopes, simply reflecting the regional slope of the ground, or is aligned to parallel structural trends.

iii) Rectangular drainage. Here, all streams are subsequent or strike streams, ie they follow lines of greater weakness. The main streams and tributaries display right-angled junctions and bends due to the influence of joints or faults.

iv) Radial drainage. This is typical of dome structures with streams radiating from a central area.

v) Centripetal drainage, which is the antithesis of radial drainage. Here, all streams flow towards a central area.

Most drainage networks occurring in the area conform to one of these patterns on a local scale while, on a larger scale, networks are a variation on one of these forms or a mixture of them. Each of these patterns of development of the drainage system indicates the presence of a certain type of structure or bedrock within the catchment.

In general, the Alfios river drainage system can be considered as showing a centripetal pattern in which the various tributaries flow towards the subsided Megalopolis basin. On a regional scale, a rectangular or parallel or dendritic pattern of development is clearly distinguished, although, over larger areas, a pattern of development made up of a mixture of the dendritic, the rectangular and the parallel patterns is observed.

On the western side of the Alfios river, a dendritic to parallel pattern of development is generally dominant. A parallel pattern of development is also present in the central to northern part of the catchment. The greater part of the Elisson tributary, around the Piana village, where it flows over an extensive almost uniform outcrop of the carbonate rocks of the Tripolis zone, has developed a characteristic rectangular pattern.

Faulting was the predominant, perhaps even unique, determining factor controlling the development of the drainage system here, with the branches arranged along the major fault zones. The eastern part of the Alfios stream, as around the village of Manaris, together with the Kutifarena stream, is developed in rectangular to parallel patterns, while the Xerilas tributary is mostly developed in the dendritic pattern, although a rectangular pattern is evident in places.

Other patterns of development, indicating the presence of particular morphological or structural features within the Alfios drainage basin, are only of local importance. An example is the radial pattern of development which was recognised in the central part of the catchment of the Xerilas tributary and also south of the village of Arachamites.

8.2 Total rainfall

Three methods were used for the calculation of the total mean annual rainfall over the catchment of the Alfios river. These were: a) the arithmetic mean method, b) the Thiessen method, and c) the isohyetal method.

a) The arithmetic mean method

As its name implies, this is obtained by dividing the sum of the rainfall at all the stations by the number of stations. A satisfactory estimate is obtained only when precipitation is relatively uniform over the basin and the stations are distributed in a regular manner.

The mean annual rainfall over the basin of the Alfios river was 1,107 mm for the period 1962-77 (Table 8.1, Appendix Ia). Thus the total mean annual rainfall over this basin, calculated by the formula $Pt = A \times Pm$ (8.1), where Pt = the total mean annual rainfall over the basin, A = the area occupied by the basin and Pm = the mean annual rainfall over the basin, was computed as Pt = 871 (km^2) x 1,107 (mm) = 964.2 x $10^6 m^3/yr$.

b) Thiessien method

This method is more sophisticated than the former in its application. It assumes that a linear variation in rainfall exists between the stations. The adjacent stations located on the map are joined by straight lines, thus dividing the whole area into a series of triangles. Perpendicular bisectors are erected on each of these lines, thereby forming a series of polygons around each station (Fig

No.	Rainfall station	Measured mean annual rainfall 1962-77 (mm)	Polygon area surrounding the station (km^2)	Total mean annual rainfall over the polygon area surrounding each station ($\times 10^6 m^3$)
1	Akovos	1454	66.3	96.40
2	Arachamites	1108	56.7	62.82
3	Vytina	1066	10.3	10.98
4	Ekklisoula	1211	22.2	26.88
5	Zoni	928	59.8	55.49
6	Karytena	972	58.2	56.57
7	Manaris	963	36.0	34.67
8	Megalopolis	863	50.8	43.84
9	Neochon (Lyk)	1160	69.4	80.50
10	Paparis	1154	44.0	50.78
11	Potamia	1018	93.4	95.08
12	Silimna	1068	13.4	14.31
13	Souli	1097	12.6	13.82
14	Chranoi	1170	25.3	29.60
15	Karatoulas	1030	66.3	68.29
16	Kardaras	1323	14.1	18.65
17	Mallota	1205	47.5	57.24
18	Roino	1061	53.3	56.55
19	Tseplakos	1174	70.9	83.23
	Total	-	870.5	955.70

Table 8.1 Data for calculation of the total mean annual rainfall over the Alfios river catchment by the Thiessien method.

Fig. 8.3: THIESSIEN POLYGONS

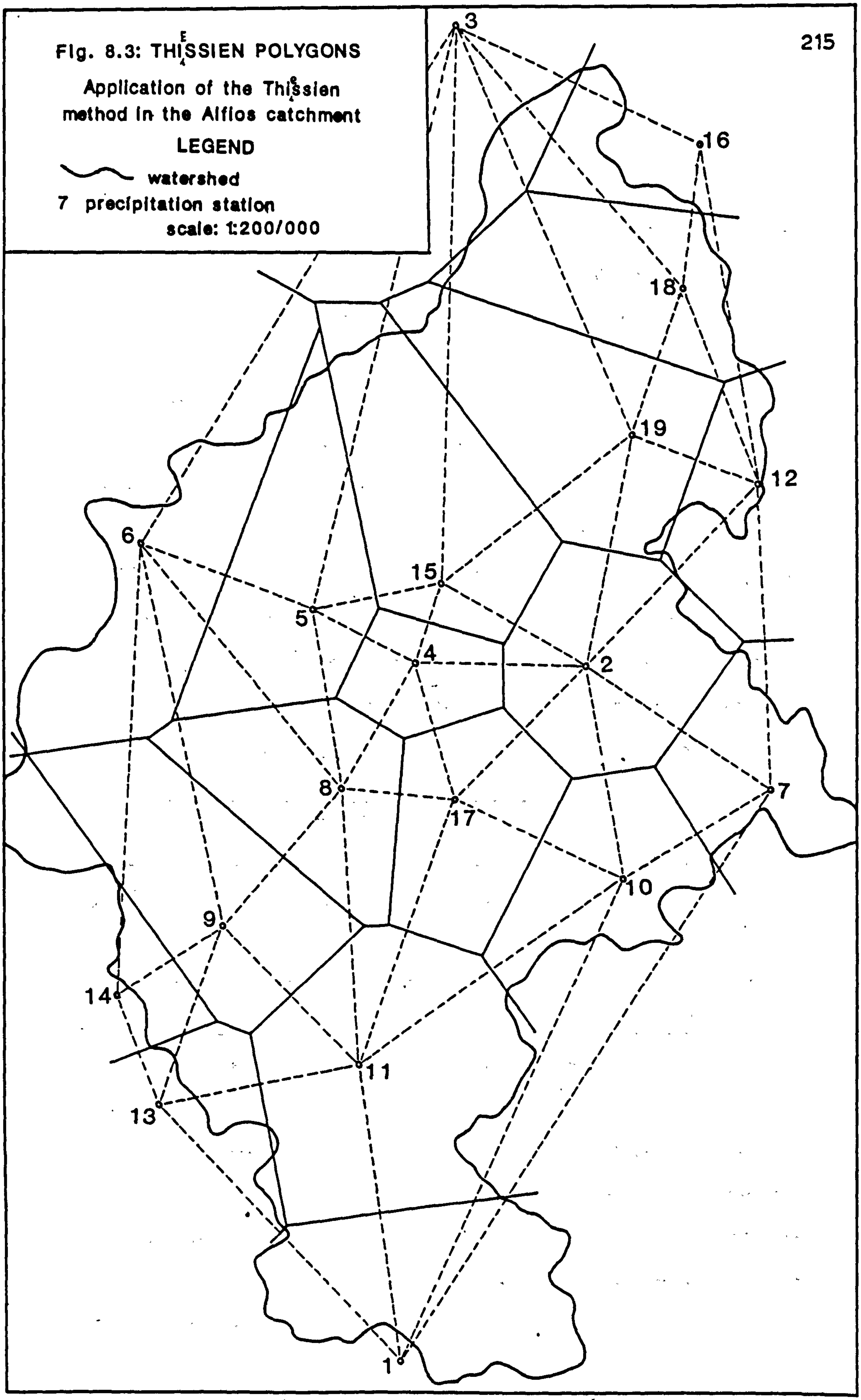
Application of the Thiessien method in the Alfios catchment

LEGEND

watershed

7 precipitation station

scale: 1:200/000



8.3). The total mean annual rainfall (Pt) over the basin is then calculated from the equation $Pt = A_1P_1 + A_2P_2 + \ldots A_nP_n$ (8.2) where $P_1, P_2, \ldots P_n$ represent the mean annual rainfall at the stations whose surrounding polygons have areas $A_1, A_2 \ldots A_n$. These data are given in Table 8.3. By replacing them into the above equation (8.2) the total mean annual rainfall was found to be $\overline{P}t = 970.55 \times 10^6 m^3/yr$.

c) The isohyetal method

First, the isohyetal map of the catchment is drawn by drawing the isohyets or contours of equal rainfall (Fig 7.6). By planimetering the areas between adjacent isohyets, the total rainfall over the catchment can be calculated from equation (8.2) in which $A_1, A_2 \ldots A_n$ now represent the areas between the successive isohyets and $P_1, P_2 \ldots P_n$ represent the mean annual rainfall of the respective areas. By inserting the data listed in Table 8.2, it was found that $Pt = 983.49 \times 10^6 m^3/yr$.

Isohyets (in mm)	Mean annual rainfall (P_i) (in mm)	Area (A_i) (in km^2)	Total mean annual rainfall (in $10^6 m^3$)
Over 1400	1500	37.7	56.55
1400-1200	1300	238.7	310.31
1200-1000	1100	405.2	445.72
Below 1000	900	189.9	170.91
Total	-	871.5	983.49

Table 8.2 Data for calculation of the total mean annual rainfall over the Alfios river catchment by the isohyetal method.

<u>Note</u>: For those areas for which a isohyetal value 'over 1400 mm' or 'below 1000 mm' is shown, the mean annual rainfall value for those areas was taken to be equal to 1500 mm or 900 mm respectively, as these areas must be surrounded by a higher or lower isohyet.

As can be seen from Table 8.3, only small differences appear to exist between the figures calculated for the total mean annual rainfall over the Alfios catchment when the three methods described above are applied. This is due mainly to the relatively large number of precipitation stations existing within the area and also partly to its relatively mild relief.

Method	Arithmetic mean	Thiessien	Isohyetal
Total mean annual rainfall over the Alfios basin x $10^6 m^3$	964.20	955.70	983.49

Table 8.3 Total mean annual rainfall over the Alfios catchment calculated by various methods.

In general, the isohyetal approach is the most preferable method of computing the total mean rainfall over an area, since it takes into account factors affecting precipitation (eg topography).

According to Sanderson and Johnstone (1953), the determination of the mean precipitation over an area is much more accurate if isohyetal maps are used, as they take into account the "spatial relationship" factor. The standard error is much greater, depending on the size of the area and also the number of stations (gauge spacing), when the Thiessien method is used for calculations from the same basic data. However, it is noticed in the Sanderson and Johnstone report (op. cit.) that "the increase in accuracy achieved by use of the isohyetal maps tends to offset the decrease in accuracy that results from irregular spacing to such an extent that the results obtained from an isohyetal map based on gauges spaced 'at random' are of the same order of accuracy as the results obtained from the Thiessien computation for an area of the same size containing uniformly spaced gauges."

8.3 Infiltration

The infiltration capacity of a given terrain, including soil cover, is the maximum potential rate at which it can absorb rain as it falls (Horton, 1933 and 1945). Infiltration capacity is governed by physical laws and processes which involve the simultaneous downward flow of water, firstly bringing the soil moisture to its maximum level and then reaching the water table, and the upward flow of displaced air through the same system of soil pores.

The infiltration capacity is controlled by a number of factors:

a) The lithology (texture and structure) of the outcrop and in particular of the soil cover (eg the presence of biological structures, the degree of compaction, the proportion of clay minerals).

b) The degree and the type of vegetation.

c) Moisture content of the soil and thickness of the aeration zone.

d) Condition of the soil surface (eg newly cultivated, baked or sun-cracked).

e) Other factors of less importance (eg temperature).

It is also noticed that the infiltration capacity of a given area is not constant during rain and is usually reduced at the beginning of the rain by the effects of the rain falling (ie packing of the soil surface, swelling of the colloids and washing out of fine materials into the larger pores in the soil surface).

The coefficient of effective infiltration, defined as the amount of water actually infiltrating out of the total rain as it falls, is also affected by a number of factors which control the rates of surface run-off and evapotranspiration and the amount of rain lost through them, thus determining the amount of water available for infiltration. These factors are: the land slope, the rainfall regime (intensity), rainfall distribution throughout the year, temperature, winds, air humidity and other factors (see also Sections 7.3 and 8.4).

Various methods and formulae for estimating the coefficient of effective infiltration (Ie) have been developed. Those most commonly used are:

a) **Direct methods for estimating the Ie**

i) by using lysimeters, which give the infiltration rate at a given point. This method cannot be applied where the water movement takes place through fissures and channels (the conduit type of groundwater movement), for there is a high degree of heterogeneity in the factor of infiltration (eg in fractured rocks, especially limestones).

ii) from the total yield of the springs using the formula:

$$Ie = \frac{Vs \pm \Delta V}{Vp}$$

where Vs is the amount of water discharged by the spring during a hydrological cycle of time, Vp is the amount of rainfall over the area feeding that spring and ΔV represents any change in groundwater storage. Here, the accurate determination of the area feeding the spring is necessary, as well as proof that the feeding area is not in hydraulic continuity with other aquifers and that points of discharge other than the main spring (eg seepage points, submarine springs, water abstraction) do not exist, or else it is necessary to obtain adequate data to calculate the amount of water entering or leaving the aquifer feeding the spring in question. Finally, complete records of the spring's discharge covering a period of several years are necessary.

iii) from the annual discharge rate of the spring by calculating the recession coefficient. Here also, the accurate determination of the aquiferous area feeding the spring is required. This method resembles that used for calculating the base-flow of a river.

iv) by using formulae based on long-term experimental data, such as those developed by Kessler (1965).

b) Indirect methods for estimating the Ie

i) A common method used is to assume that infiltration equals the amount required to make up the total values of the hydrological balance of the catchment. This method is prone to some error and the results can be considered unreliable to a certain degree as, for the calculation of the other parameters involved in the hydrological balance, empirical formulae are used (as for evapotranspiration, see Section 7.3). This method is also frequently unreliable due to lack of data or information which leads to assumptions and approximations being made. The degree of unreliability under these circumstances increases with the size of the catchments in question as the heterogeneity and the complication of the factors affecting the water balance are greater for larger catchments. For smaller catchments, on the other hand, an accurate evaluation of the existing data can give reliable results.

ii) Secondly, in cases where it is not possible to calculate the coefficient of the effective infiltration, those coefficients calculated for similar formations or for basins of a similar geological make-up are often used.

An attempt was made at calculating the coefficient of the effective infiltration for the Pindos zone limestones by using the formula

$Ie = \frac{Vs + \Delta V}{Vp}$ and applying it to the Palataki spring for which some recharge data were available. This spring is fed from an individual small limestone outcrop of the Pindos zone, the extent of which is well defined. For the rainfall data, the mean arithmetic value of the rainfall recorded at the Karytena and Megalopolis stations over the corresponding period was used, while changes in groundwater storage were not taken into account as these are generally considered to be small and may effectively be ignored when working on a yearly basis.

The data used and the resultant infiltration (Ie) values are given in Table 8.4.

Hydrological Year	Mean annual precipitation (in mm)	Total precipitation (x 10^5 m^3)	Total discharge (x 10^5 m^3)	Infiltration (%)
1962-63	1315	36.2	23.0	63.5
1963-64	856	23.5	12.4	52.8
1964-65	955	26.3	18.5	70.3
1965-66	970	26.7	14.1	52.8
1966-67	910	25.0	8.3	33.2
Mean	1001	27.5	15.3	54.5

Extent of the area feeding the spring = 2.75 km^2

Table 8.4 Calculation of the effective infiltration coefficient of the limestones of the Pindos zone by using data for the Palataki spring.

In order to calculate the total annual discharge of this spring, its discharge graph was used (Fig 10.2) by planimetering the area between the base of the graph (zero discharge) and the discharge fluctuation line. It should be noted that a great degree of error is involved in this calculation due to the fact that the discharge values available for the spring are rather sparse and are, therefore, to a certain extent insufficient. Furthermore, after a heavy winter storm, an intermittent spring results from the outcrop feeding the Palataki spring, issuing 1 km SW of the village of Mavria, according to the local people. If this is so, a lower Ie value than the actual has, therefore, been calculated for the limestones feeding the Palataki spring.

It should be understood that because of the limitations and uncertainties described above, the Ie value (55%) calculated for the Upper Cretaceous limestones of the Pindos zone can only be taken as a rough value, not very closely representative of the actual situation, although the value of 55% calculated is feasible.

Marinos (1975) reported that the effective infiltration coefficients for the karstic areas of Greece, with a small or even nil percentage of impermeable rock cover, average between 0.40 and 0.55. These values were obtained during various hydrological studies carried out by different investigators for karstic areas of Greece by using the direct methods outlined above. Based on these studies, he also concluded that the direct run-off in the karstic areas of Greece is very low (0.01 to 0.1, as a percentage of the total precipitation), even after heavy winter storms.

Data on the effective infiltration do not exist for the carbonate rocks of the Tripolis zone in the wider area and it was not possible to calculate the effective infiltration by using any of the direct or indirect methods described above.

Due to the complex geological make-up of the catchment of the Alfios river (metamorphic rocks, carbonate rocks, flysch, superficial basin sediments) and the complicated structure within it (successive alternations of impermeable and permeable bands of rocks, especially in its western part) an accurate individual calculation of the effective infiltration coefficient for each type of rock is impossible.

The calculation of the effective infiltration coefficient for the catchment of the Alfios river as a whole indirectly, by equating the base flow of the Alfios river to the amount of water infiltrating the various formations of the basin, is not valid, as the carbonate rocks of the Tripolis zone and also part of the limestone of the Pindos zone discharge outside the basin of the Alfios river (for details, see Section 8.5).

8.4 Run-off

8.4.1 Total run-off of the Alfios river

The total run-off, also referred to as catchment yield or total discharge of a stream, is normally expressed as a volume per unit of time (usually year). It originates from the direct run-off (surface run-off + interflow) and from the groundwater contribution, ie base flow of the stream or river (see also Section 8.4.2).

The run-off is affected by many factors:

a) Climatic, such as the total annual rainfall over the drainage basin, its distribution throughout the year, the intensity and duration of the rainfall, and those factors affecting evapotranspiration and infiltration (see Sections 7.3 and 8.3).

b) Topographical features of the catchment and also of the drainage system, such as the size and shape of the basin, the ground slope and the texture of the drainage system, ie its frequency (total number of streams per unit area) and its density (total length of the streams per unit area). It is noticed here that the topographic divide and the groundwater catchment may differ greatly, thus affecting the base-flow portion of the streams.

c) The geological make-up of the catchment rock types and the distribution of the permeable and impermeable formations within it, as well as the presence and nature of the soil cover.

The first two factors (a and b) govern, to a certain extent, the amount of direct run-off, while the third (c) determines mainly the base-flow contribution to the stream or river.

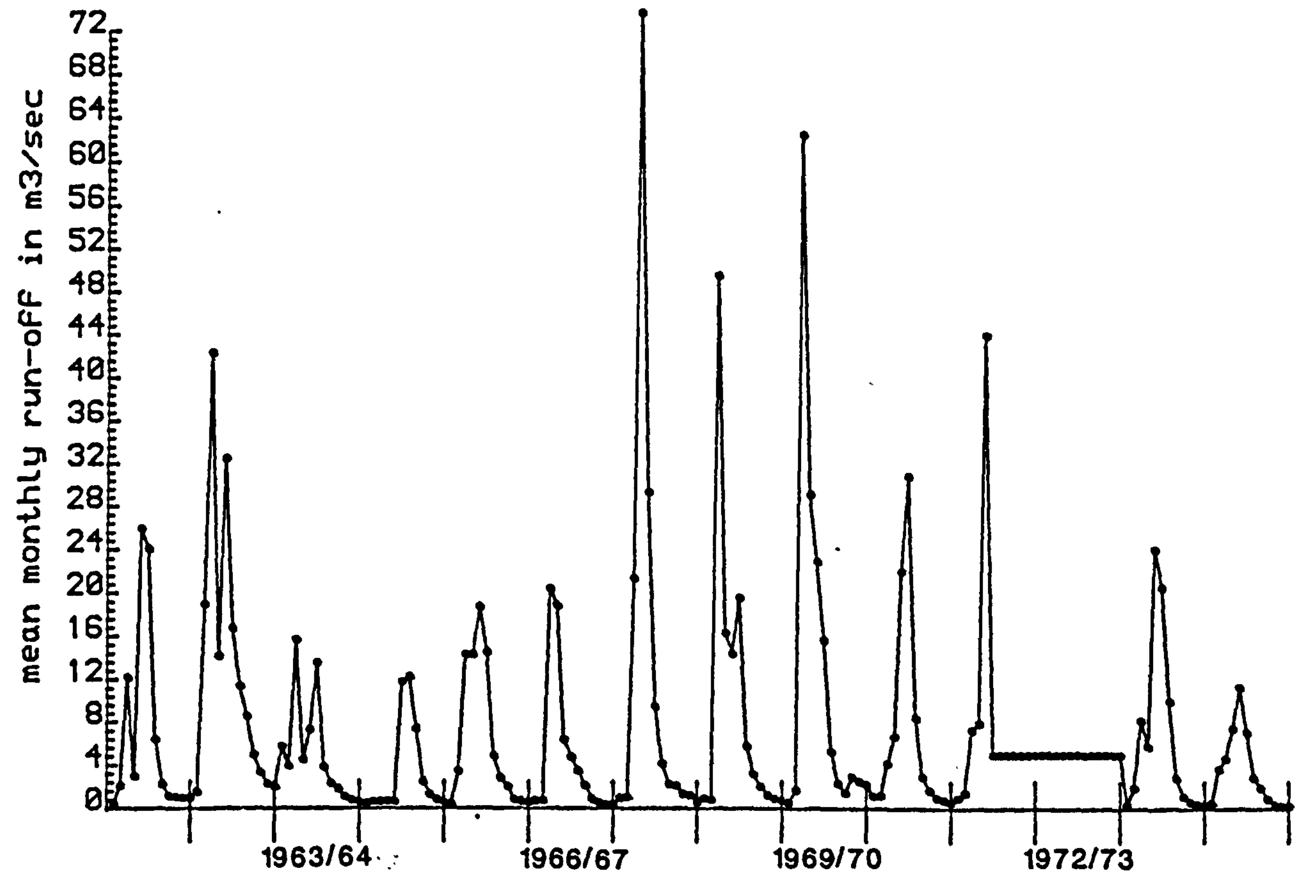


Fig 8.4 Hydrograph of the Alfios river mean monthly run-off recorded at the Karytena gauging station during the period October 1962 - September 1976.

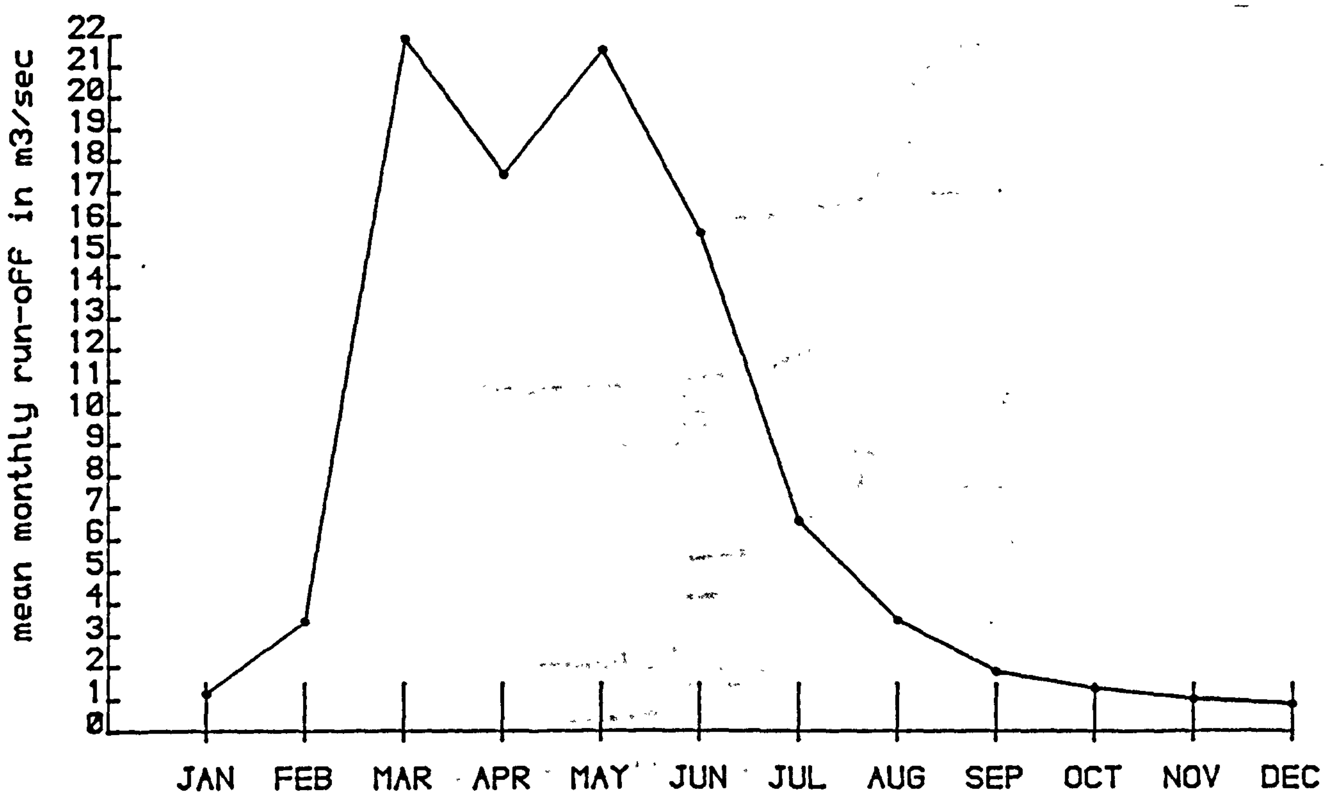


Fig 8.5 Hydrograph of the mean monthly run-off (mean values) of the Alfios river recorded at the Karytena gauging station during the period 1962-76.

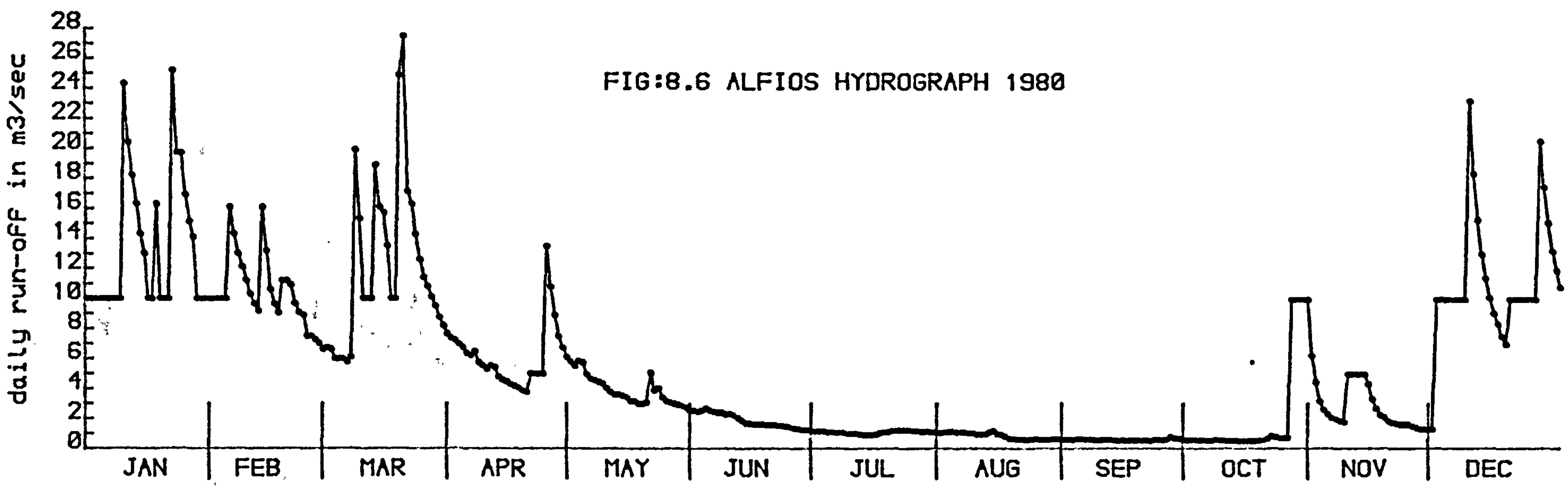


FIG:8.6 ALFIOS HYDROGRAPH 1980
daily run-off in m3/sec
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

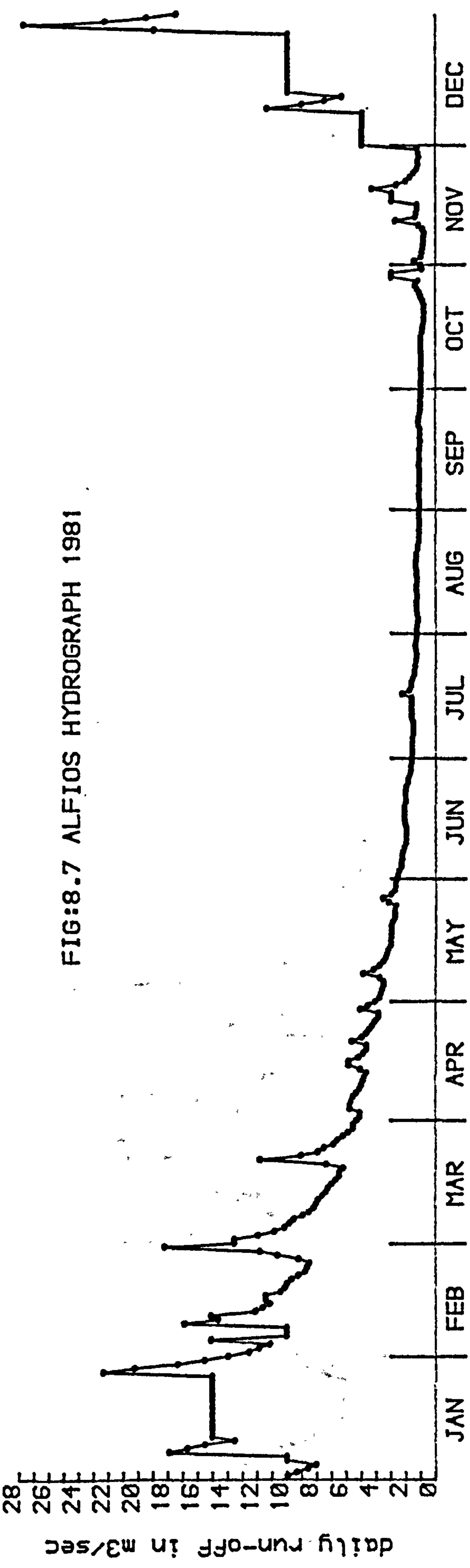


FIG:8.7 ALFIOS HYDROGRAPH 1981

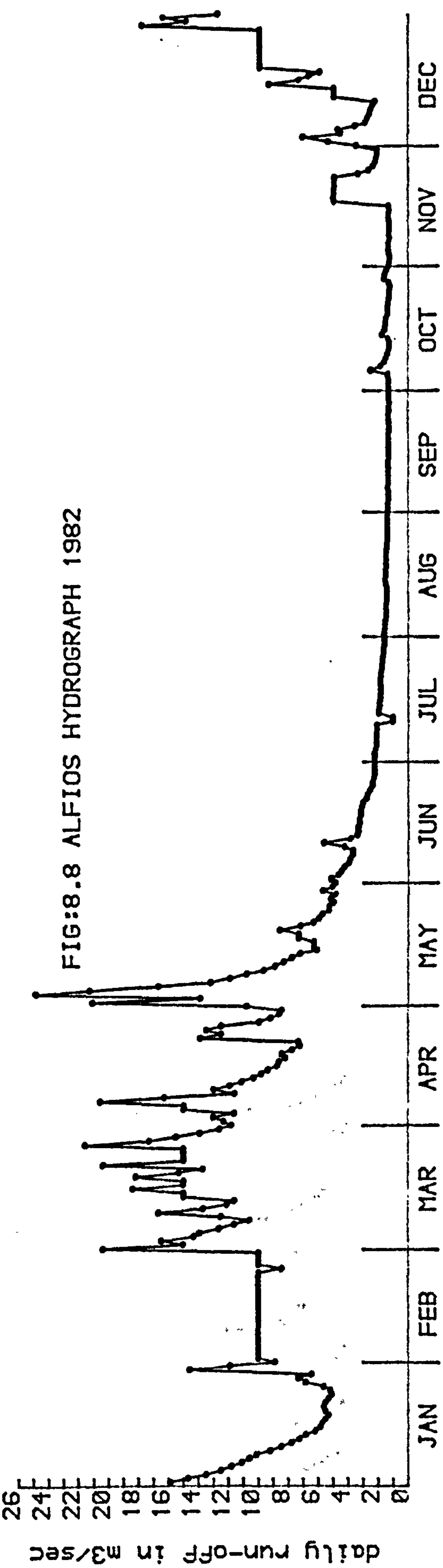


FIG:8.8 ALFIOS HYDROGRAPH 1982

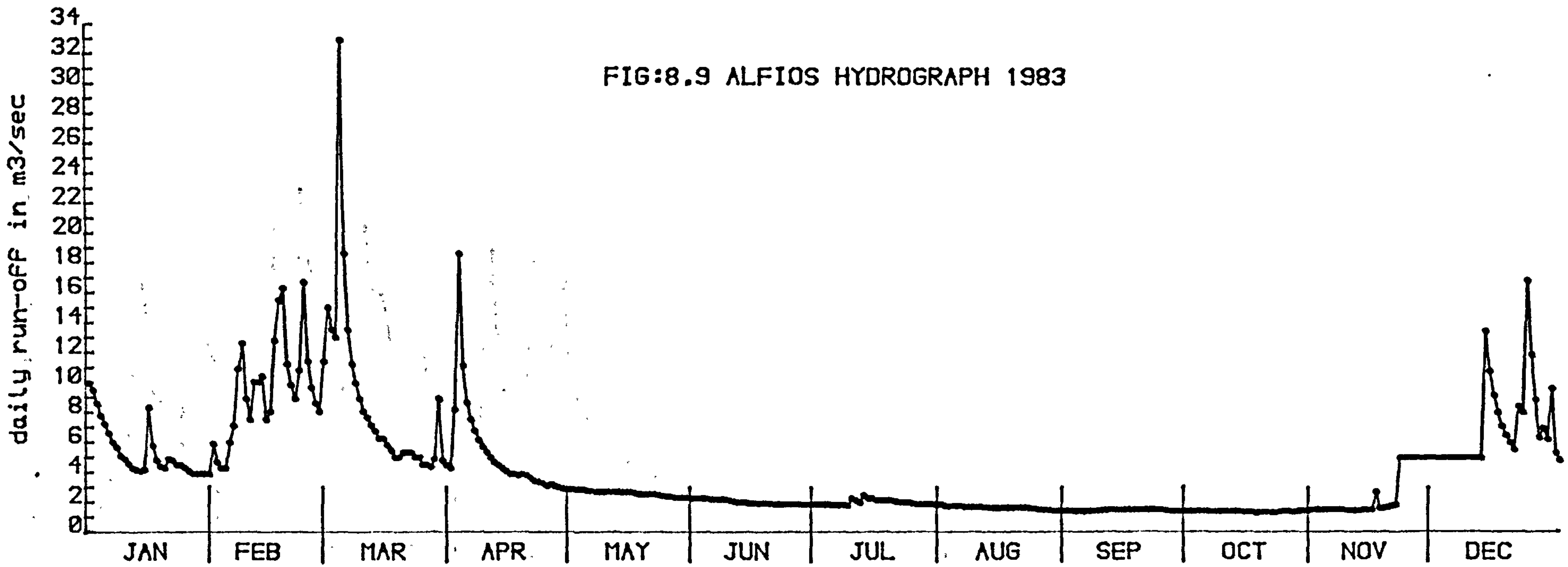


FIG:8.9 ALFIOS HYDROGRAPH 1983

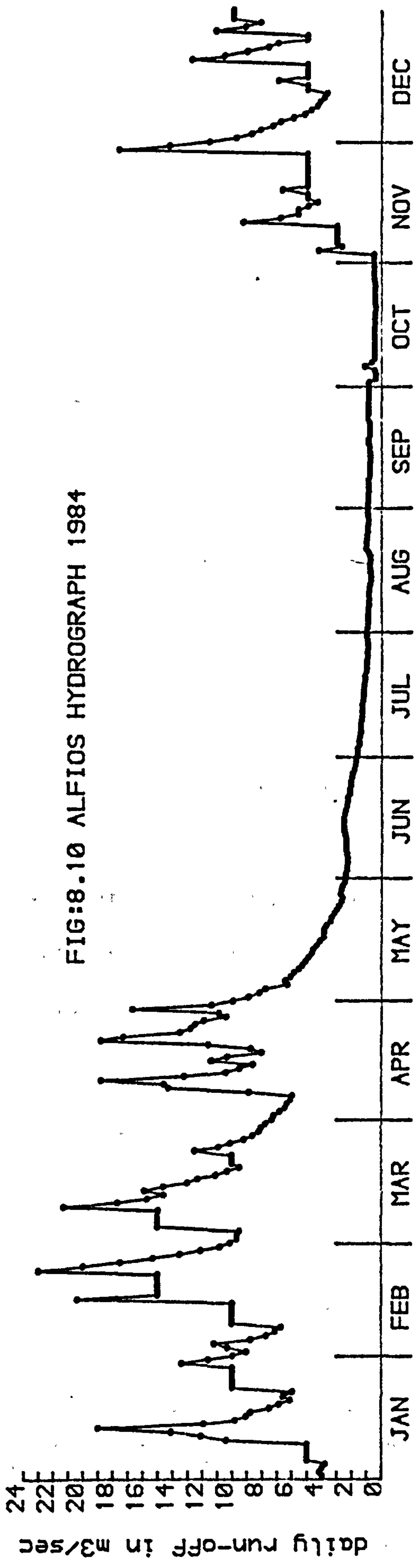


FIG:8.10 ALFIOS HYDROGRAPH 1984

The total run-off of the Alfios river for the period 1962-76 is given in the hydrograph of Figure 8.4 where the mean monthly run-off values (mean values of the discharge rates recorded on a daily basis at the Karytena gauging station, given in Appendix II) are plotted against time. In Figure 8.5, the mean values of the mean monthly run-off of the Alfios river recorded at the bridge at Karytena are given in the form of a hydrograph for the period 1962-67, while in Figures 8.6 to 8.10 the hydrographs of the daily discharge of the Alfios recorded during the years 1980-1984 inclusive are shown.

In Figure 8.11, the sparse irregularly-taken measurements of the Alfios river at the bridge on the road from Megalopolis to Kalamata are given in the form of a hydrograph for the period 1965-67. It can be seen that the discharge of the Alfios river measured here is much lower than the accumulated discharge of the tributaries contributing to its flow upstream from this bridge, ie the Alfios (Gianoremma), the Kutifarena and the Xerilas streams (see Figs 8.15 and 8.16). As these tributaries flow over the impermeable basin sediments, the only possible explanation for this is that the measurement of their discharge did not take place at the same time (ie on the same days).

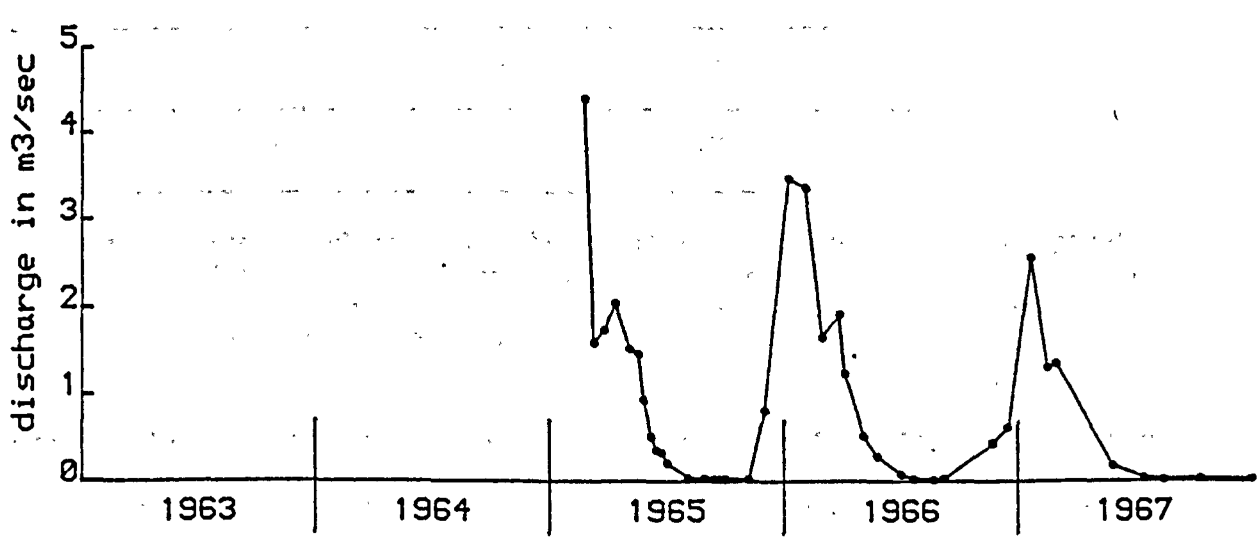


Fig 8.11 Incomplete hydrograph of the daily run-off of the Alfios river recorded at the bridge on the Megalopolis-Kalamata road (1965-67.)

A quantitative expression of the run-off in the form of a coefficient is obtained by dividing the total run-off of the catchment by the total precipitation over the catchment for the corresponding period.

The coefficient of the total run-off for the Alfios river catchment has been calculated for the period 1962-75, for which the necessary data were available (Appendix II). For the Alfios river run-off, mean monthly discharge rates taken at the bridge of Karytena during the period are available (Fig 8.1), while the total precipitation was calculated for each year by using the 'arithmetic mean' method (Section 8.2) and the data from Appendix Ic.

Hydrological year	1962-63	1963-64	1967-68	1968-69	1969-70	1970-71	1973-74	1974-75	Mean
Total run-off $m^3 \times 10^6$	416.37	162.06	390.68	303.03	393.09	212.39	197.33	107.36	2182.31
Total precipitation $m^3 \times 10^6$	1319.74	887.98	1056.09	920.30	1083.87	961.41	939.20	766.92	7935.51
Run-off coefficient %	31.5	18.3	37.0	32.9	36.3	22.1	21.0	14.0	26.6

continued ..

Table 8.5 Evaluated data for the total run-off and total precipitation for the Alfios river catchment for certain hydrological years of the period 1962-75 and the calculated coefficient of the run-off for this catchment.

From Table 8.5, it can be seen that the run-off coefficient is higher during years with low precipitation and also that the calculated mean total run-off coefficient of 27% for the Alfios catchment is relatively low. This may be due firstly to the fact that the evapotranspiration, calculated as 68% for the basin of Megalopolis and 60% for the basin of Assea, is rather high and, secondly, to the fact that a relatively large part of the underground water which should contribute to the Alfios river base-flow discharges outside the Alfios catchment (see Section 8.5).

8.4.2 Analysis of the flow character of the Alfios

A hydrograph is the graphical representation of the rate of discharge of a stream or river over a period of time. It includes the integrated contributions of the surface or overland run-off, channel precipitation, interflow and groundwater flow or base-flow. An analysis of a hydrograph provides a quantitative solution of these components, each of which has different recession characteristics (Fig 8.12).

The surplus of the rainfall which is not subject to infiltration (this depending largely upon the intensity of the rainfall), not taking into consideration interception and evaporation losses, accumulates and flows from the area as surface run-off. In general, channel precipitation (ie the amount of water that falls directly on the surface of the streams) is not considered as a separate component of run-off, since it is usually a relatively small amount and, furthermore, it overlaps with and shows similar discharge characteristics to surface run-off.

The interflow component is equal to that amount of water infiltrating through the soil surface and moving laterally beneath its surface - through the upper horizon of the soil or, perhaps, at the bedrock interface - and either returning to the surface at some point downslope to continue to flow into the stream as surface run-off or being discharged into the stream channel. This water does not become part of the characteristic groundwater flow system, as it is discharged to the river relatively rapidly.

The base-flow or groundwater component of a stream originates from that part of the infiltrating rainfall which finds its way to the saturated zone, reaches the water table, moves down the hydraulic gradient and is recharged into the nearest stream point. Its discharge takes place over a much longer period of time, since groundwater flow velocities are less than those of overland flow.

The base-flow of a stream or a river can be defined as the discharge when surface run-off and the volume of channel storage have become negligible. It differs from groundwater discharge only by the amount of water lost through evapotranspiration. For most hydrological studies, the base-flow component of a stream hydrograph is the most important component to determine as, to a certain extent, it defines the total underground water yield of the catchment.

However, the effluent or influent character of the stream (ie direction of water movement away from or towards the stream channel respectively) should not be overlooked. This is dependent on time, as the relative positions of the water table level in the adjacent aquifers and the water level in the stream show temporal variation.

Certain problems exist in defining the contribution of the groundwater discharge component to a stream or river, in other words, in determining the form of the base-flow recession curve beneath the main hydrograph during the peaks of the river's discharge and during the wet season in general, when both the direct run-off and the interflow components of the river's total run-off are also high. During the period from April to November, the Alfios river flow is considered to originate mainly from groundwater discharge (see hydrographs, Figs 8.6 to 8.10).

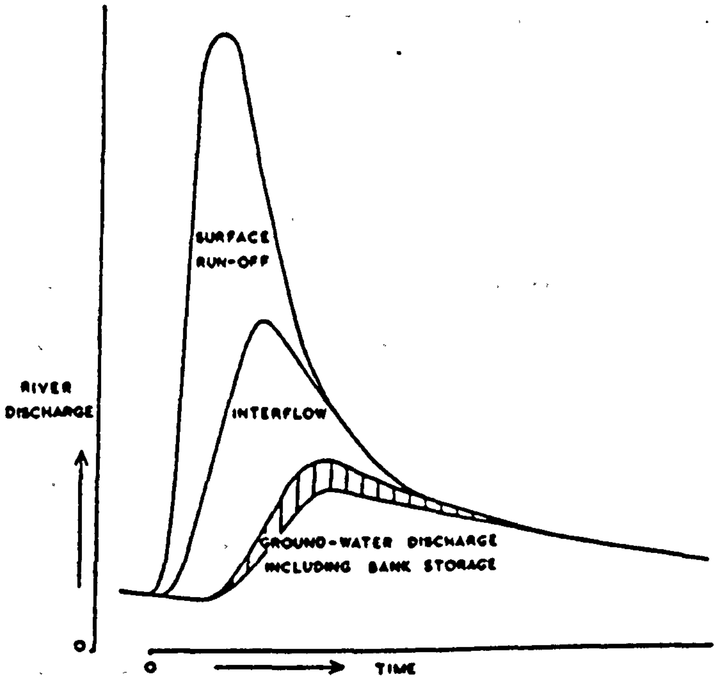


Fig 8.12 Schematic diagram of components of river discharge (run-off). The vertically ruled area represents the bank storage contribution to groundwater discharge (after Ineson and Downing, 1964).

Several graphic techniques have been developed for the determination of the various flow components making up the hydrograph of a stream or river. Each method possesses certain advantages, depending on the type of investigation being carried out and also on the geology and topography of the basin, although it should be noted that all of them are arbitrary and subjective to a certain extent (Linsley et al., 1975).

The method chosen in this study to separate and distinguish the base-flow component of the Alfios river hydrograph was that formulated by Ineson and Downing (1964). According to this method, the previous groundwater recession extends to a minimum immediately under peak run-off, resulting from a well-defined period of precipitation and then rising to a maximum within a certain interval of time. This was established by extending the recession curves beneath the rising and falling limits of the main hydrograph. The interval of time after which the bulk of the direct run-off has been discharged depends predominantly on the size of the catchment and was calculated by using the following empirical equation (Linsley et al., 1975)

$$N = 1.25\ A^{-0.2}$$

where N = the time interval in days and A = the area of the basin in km^2. For the Alfios river catchment, which comprises a drainage area of approximately 870 km^2, a figure of 4.8 days was calculated.

It should be noted that this method is also subjective and that problems of identification arise when complex rainstorms occur and no single maximum run-off peaks in the curve can be identified.

The constant of the rate of recession of the flow of a river or stream is a characteristic feature of that stream or river. It is predominantly controlled by the geological and topographic characteristics of the particular drainage basin in question.

Horton (1933) and others have postulated that the recession curve for a non-artesian aquifer may be defined by a characteristic depletion equation, a convenient exponential general form of this being

$$Q_t = Q_o\ e^{-kt}$$

where Q_t is the discharge at time t after a given initial discharge Q_o and k is a recession constant that is always less than unity.

On a semi-logarithmic plot, where the logarithm of the discharge is plotted against time, according to this equation a linear relationship between these two variables may be obtained. The best straight line is generally for the groundwater recession, its slope being -k log e and the value of zero intercept, Q_o (Webber, 1961).

A straight line is always derived when the hydrogeological conditions within the basin are relatively simple. Owing to evaporation losses, including transpiration, and to the complicated hydrogeological conditions within the basins (eg contribution of groundwater of various aquifers or aquifer systems with different hydraulic properties) and possibly also to other factors, such as differing permeability of portions of the aquifer or infiltrated precipitation during summer, a straight line is not always obtained, this non-linear sequence suggesting a continuously changing set of conditions. Even in such cases, when shorter periods of the total recession period are considered, a series of straight lines fitting best to the respective parts of the recession curve, although not necessarily parallel to each other, may be constructed. A series of recession constants, each one corresponding to the respective part of the recession, can therefore be calculated.

The Alfios river derives its base-flow from the groundwater discharge of the two main aquifer systems: (a) the Upper Cretaceous limestones, either discharging through karstic springs or directly into the river, as observed in the vicinity of the Kyparissia field, and (b) the aquifers developed in the permeable parts of the unconsolidated sediments filling the basin and the terrace gravel-bodies spread along the river system.

A study of the Alfios river hydrographs for the period 1980-1984 (an example is given in Fig 8.13) shows that at least two non-parallel straight lines can be drawn to fit best successive parts of the recession curve of these hydrographs and, consequently, two recession constants can be calculated for these two successive parts of the recession period. The first part of the recession period comprises the months from April to July, during which the bulk amount of the bank storage water from the terrace gravel-bodies and from the karstic aquifers, ie karstic springs and overflow, is contributed to the Alfios river base-flow. A greater recession constant is always calculated for this period (see Table 8.6). The second part of the recession period lasts from July to November and represents a stabilising period of the Alfios river base-flow. A lower recession constant of approximately 0.003 is calculated for this period

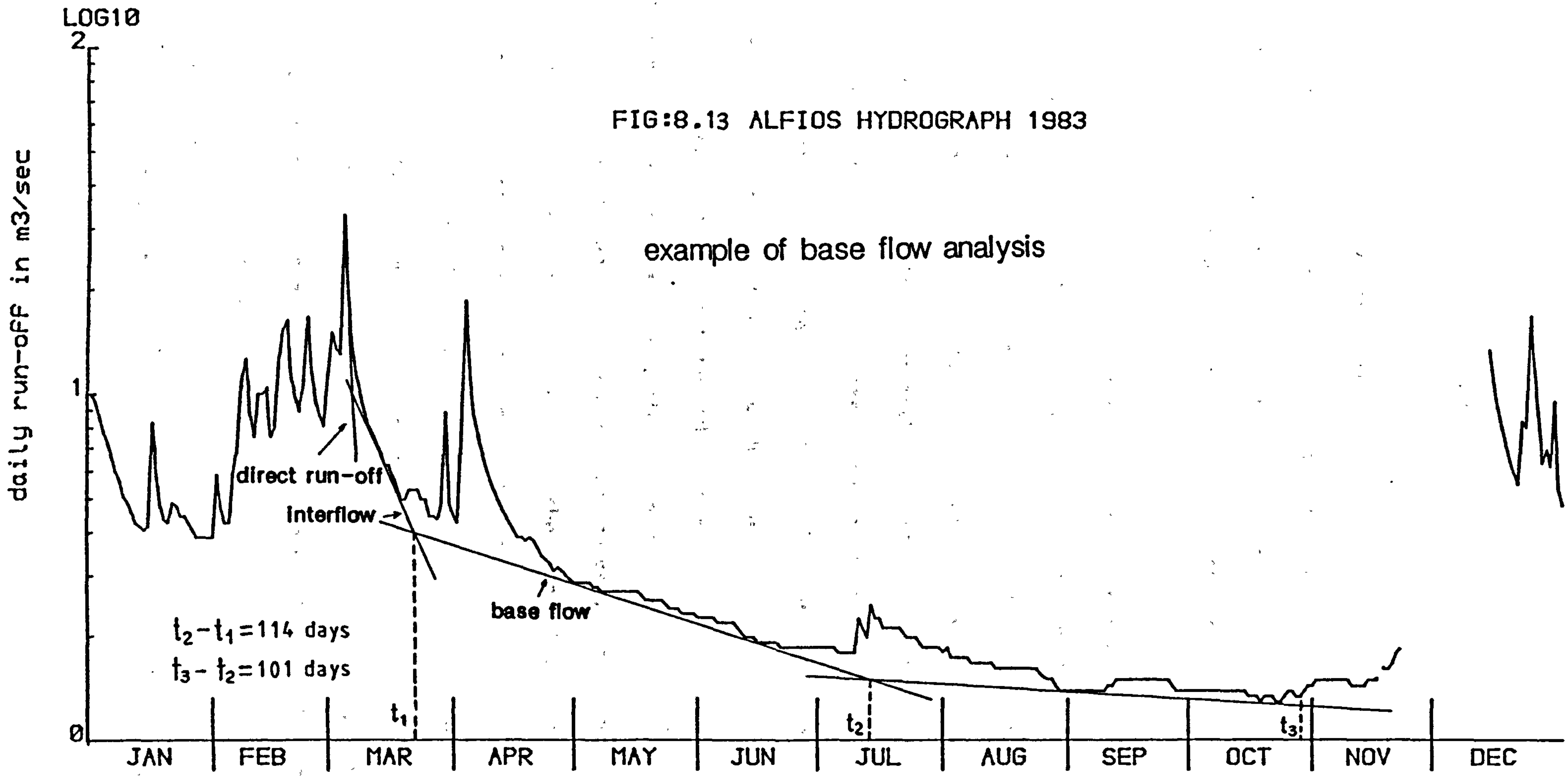


FIG:8.13 ALFIOS HYDROGRAPH 1983

during which the water is contributed mainly from aquifers developed in the lowly permeable, unconsolidated basin sediments.

The recession period for the Alfios river, during which all or almost all of its flow originates from groundwater discharge, generally lasts from March or April to November, depending on the precipitation distribution for the year. The duration of the recession period averages from 6 to 8 months, a mean figure of 209 days having been calculated for the period 1980-84 (Table 8.6).

'Flash' peaks are only present during the recession period in the early spring (March and April) and in the late autumn (November). During the period from late April almost to the end of November, the recession curve is smooth and fairly flat. Rare summer storms are barely reflected in the river's hydrograph, only small fluctuations being observed in the curve, due to the fact that the precipitation either infiltrates into the ground through the strata or evaporates, due to the high mean temperatures during this period, with almost no overland flow into the river network. During this period, almost all the Alfios base-flow (95-100%) is derived from groundwater discharge.

As the water table recedes during summer, the contribution of groundwater to the Alfios flow diminishes and this, considered in conjunction with the increased evaporation losses, including transpiration, during the summer, results in a flat gradient of the recession curve. In addition, the abstraction of a relatively large amount of water to supply the Electricity Station (approximately 1,400 m^3/h) further reduces the volume of groundwater that could contribute to the Alfios river base-flow from the karstic aquifers developed in the vicinity of the Kyparissia field.

The recession constants, together with a few other parameters calculated from the Alfios river hydrographs, for each of the years 1980-84 are listed in Table 8.6.

Year	Recession period in days			Slope		Recession constant	
	first part(a)	second part(b)	total	during period(a)	during period(b)	during period(a)	during period(b)
1980	89	83	172	-0.0040	-	0.0092	<0.001
1981	152	124	276	-0.0024	-0.0012	0.0055	0.0028
1982	58	143	201	-0.0042	-0.0021	0.0097	0.0046
1983	114	101	215	-0.0016	-	0.0037	<<0.001
1984	22	160	182	-0.0075	-0.0030	0.0172	0.0069
Mean	87	122	209	-0.0039	-	0.0091	-

Table 8.6 Data for the calculation of the base-flow of the Alfios.

The determination of the duration of the actual recession period for each year is, to a certain extent, subjective.

The recession constant (k), which defines the slope (-k log e) of a straight line drawn to fit as closely as possible to the recession curve, has a value given by the equation $k = 10^{(-1/\Delta t)}$, where Δt is the storage delay factor in days, or the time required for the flow to decrease in amount by a factor of 10 or one log cycle, which can be readily determined on the semi-logarithmic hydrograph as the time in days for one cycle decrease of Q (Singh and Stall, 1971).

Meyboom (1961) introduced the parameter Q_{tp} of the total potential groundwater discharge at the beginning of the recession period, determined as the total volume of base-flow that would be discharged during an entire groundwater recession if complete depletion were to take place uninterruptedly. Q_{tp} values can be obtained by using the equation $Q_{tp} = \frac{Q_o}{k}$ where Q_o equals the groundwater discharge at the beginning of the base-flow recession (Webber, 1961).

Of much greater importance is the parameter Q_a which equals the total base-flow volume discharge (d) during the recession period (t_1 to

t_2), given by the equation:

$$Q_a = \frac{-Q_{tp}}{10^{t_2/\Delta t}} - \frac{-Q_{tp}}{10^{t_1/\Delta t}}$$

The Alfios river dries up upstream from the Kyparissia bridge during relatively dry years. During the summer of such years, its low base-flow, only visible in a few places, runs through the recent gravel body in the river bed. At the bridge of Karytena, a few kilometres north of the Kyparissia field, on the other hand, the Alfios river always possesses a substantial base-flow (0.4-1.0 m^3/sec being the lowest values measured during the periods 1962-73, 1974-75 and 1980-84). It originates from the two karstic springs of Kefalovrisi and Korbitsi, situated in the northern part of the Megalopolis basin, and from the overflow of the karstic aquifers developed in the vicinity of the Kyparissia field, either through the Panagia and Opiste Panagia springs or directly into the Alfios river. Its base-flow also originates from the discharge of water stored in the terrace gravel-bodies.

8.4.3 Flow character of the major tributaries

The major tributaries of the Alfios join it mainly from the east (ie the Elisson and Alfios streams) or from the south (ie the Xerilas and Kutifarena streams), while only minor tributaries flow into the river from the west.

The Elisson tributary is the greatest, discharging the largest part - its subcatchment accounts for 230 km^3 - of the Alfios catchment to its eastern side. For a large distance of its total course, approximately 47 km, it flows over the highly permeable carbonate rocks of the Tripolis zone and only for the last 5 km, before it enters the Megalopolis basin, does it flow over the flysch formation of the Tripolis zone. As a result, a great part of its discharge, and possibly all of it during late summer, percolates downwards to a lower aquifer system developed in the carbonate rocks of the Tripolis zone.

In the basin of Megalopolis, the Elisson always carries water, even in the late summer. During relatively dry years with a low amount of total precipitation, its discharge takes place as interflow through the recent gravel body. The greater part of the Elisson base-flow originates from the bank storage of the terraces and from the hydraulically adjacent Megalopolis beds of low permeability. The terrace bodies developed alongside the Elisson stream are in hydraulic continuity with those of the Alfios river and thus part of their water flows directly towards the Alfios river instead of towards the Elisson, due to the existing hydraulic gradient.

The measurements of its discharge, taken irregularly during the period 1963-67, are given below in the form of a hydrograph (Fig 8.14). They are 'instant' measurements of its discharge taken at the bridge on the Megalopolis to Karytena road. It is noted here that neither this

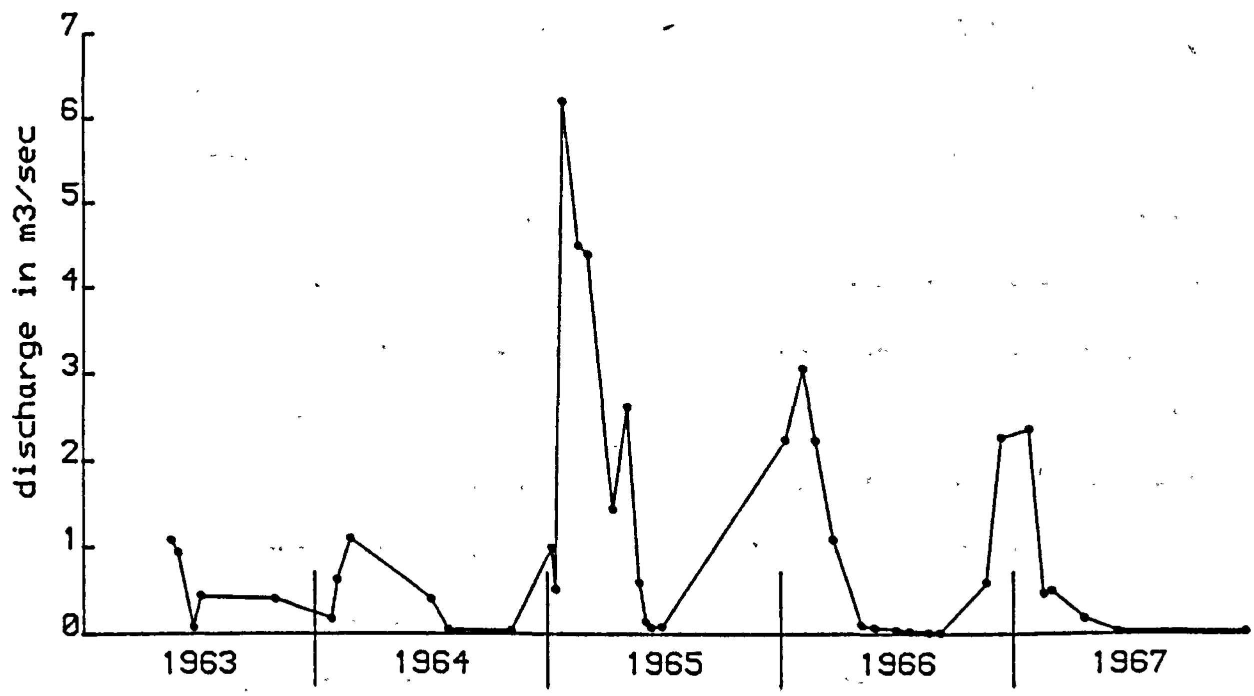


Fig 8.14 Incomplete hydrograph of the Elisson tributary for the period 1963-67 (42 measurements).

hydrograph nor those given for the other tributaries (Figs 8.15-8.18) should be considered as representative of its discharge rate during that period, as the incomplete set of measurements taken do not show the actual fluctuations of its discharge rate, many of the real peaks or minima not having been recorded.

The Alfios stream (or Gianoremma), taken as that part of the Alfios river before it joins with its first tributary, the Kutifarena, drains a large area of 114 km^2 to the eastern side of the basin of the greater Alfios river. It flows for a distance of 25 km.

Its base-flow is mainly received from the springs discharging the Upper Cretaceous limestone masses of this area but also originates from the underground water of the aquifers developed in the permeable parts of the unconsolidated deposits filling the basin of Assea, as it runs along the basin.

Data for the discharge rate of the Alfios stream are not available.

The Xerilas stream is also one of the major tributaries of the Alfios river. It discharges the southern part of the Alfios catchment and its subcatchment has a size of 142 km^2. Its total course runs for 27 km. It enters the basin of Megalopolis after flowing along an oblong graben, the Xerilas valley, close to its eastern side. Along this valley, it flows in places over the carbonate rocks of the Tripolis zone where they outcrop within the recent valley sediments while, in other places, only a thin, highly permeable bed of recent gravels exists between the river and the bedrock of the valley. As a result, a great part of its discharge percolates downwards. A small number of sink holes were observed in this area.

The sporadic measurements of its discharge taken during the period 1963-67 are given here in the form of a hydrograph (Fig 8.15).

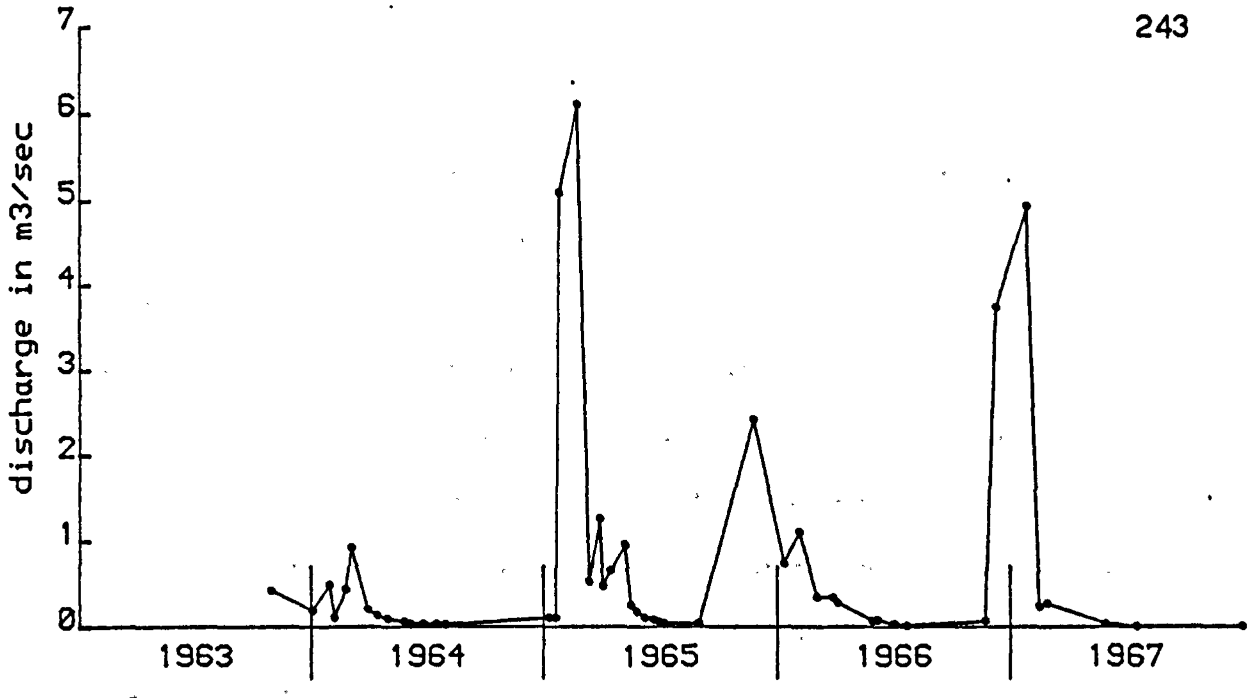


Fig 8.15 Incomplete hydrograph of the Xerilas tributary for the period 1962-67 (48 measurements).

The Kutifarena stream (or Goudanis) in the south-eastern part of the Alfios river drainage basin, discharges a subcatchment of 47 km^2 and joins the Alfiòs river after a total course of approximately 16 km. During summer, it receives most of its low flow from springs fed by the Upper Cretaceous limestone. The existing data for its run-off during the period 1964-1967 are given below in the form of a hydrograph (Fig 8.16).

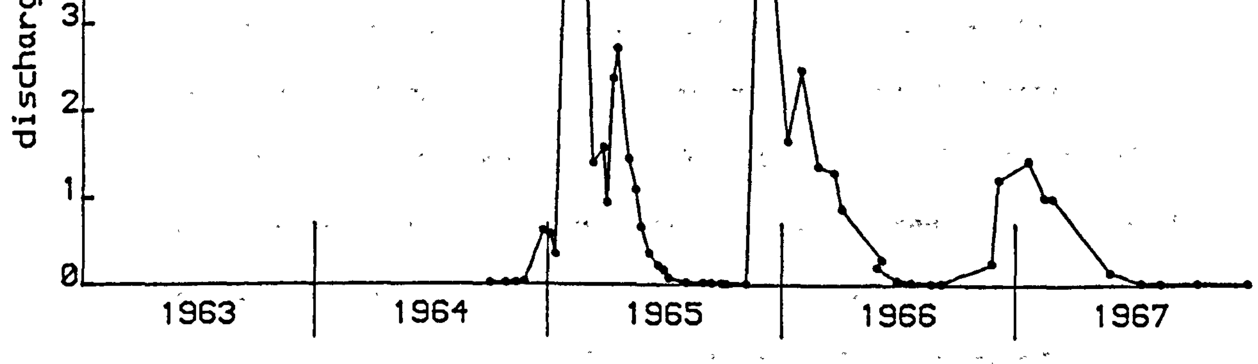


Fig 8.16 Incomplete hydrograph for the Kutifarena tributary during the period 1964-67 (51 measurements).

The Kastritis tributary flows on the western side of the Alfios river and is the main tributary on this side of the catchment. It drains a subcatchment of 40 km^2 with a total length of 11 km. It has a permanent flow during the whole year as, during summer, it receives water from various springs, such as those situated around the villages of Lykosoura, Lykaeon and Kastanochori. These springs discharge individual Upper Cretaceous limestone outcrops which belong to the successive thrust-slices in the area. The sporadic measurements of the discharge of the Kastritis tributary taken during the period 1963-67 are also given in the form of a hydrograph (Fig 8.17).

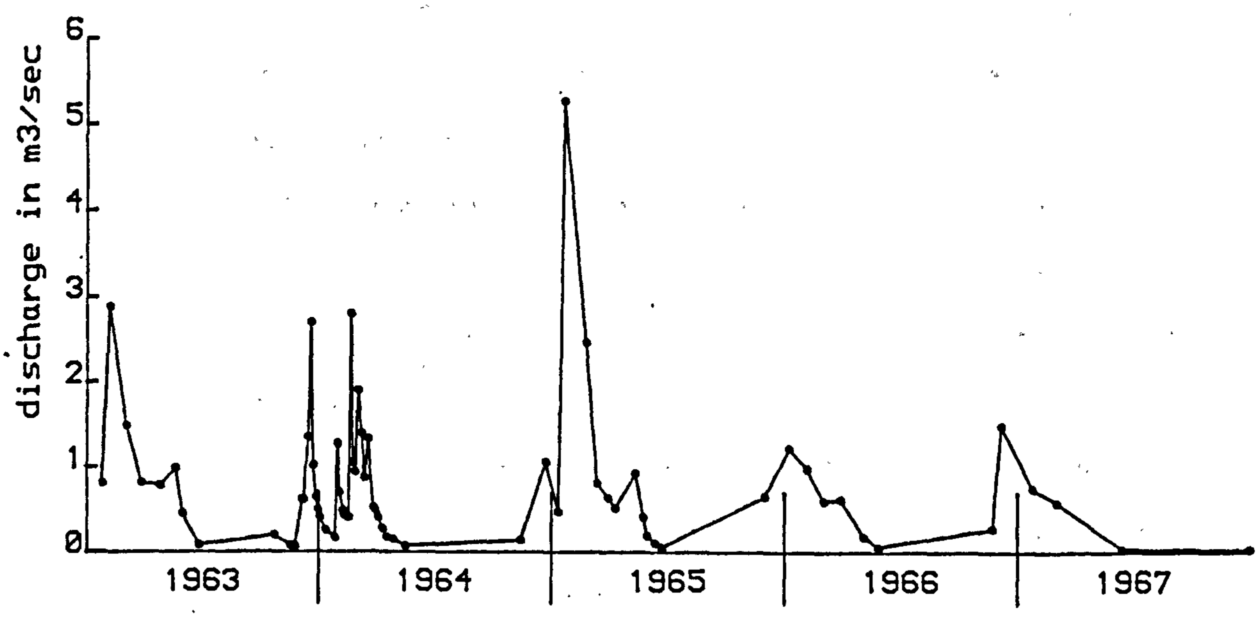


Fig 8.17 Incomplete hydrograph of the Kastritis tributary for the period 1963-67 (72 measurements).

The Valtos Choremiou tributary, lying to the south-western side of the Alfios river catchment, is another more minor tributary of the Alfios. It drains a catchment of 37 km^2 and has a length of 11 km. During the dry season, its low base-flow also originates from the karstic springs which discharge the Upper Cretaceous limestones here. The following hydrograph represents the measurements of discharge of the Valtos Choremiou tributary taken during the period 1962-67 (Fig 8.18).

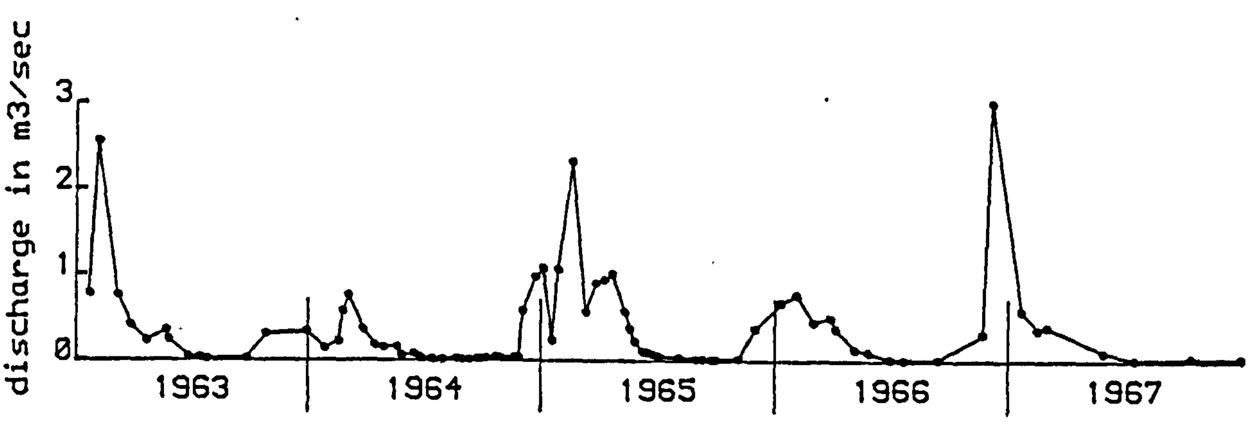


Fig. 8.18 Incomplete hydrograph of the Valtos Choremiou.tributary for the period 1963-67 (85 measurements).

The Lagadas (or Soulou), the Lapatou and the Sfikas minor tributaries, in the north-eastern part of the Alfios catchment, are all intermittent (winter) streams. Even in years with high rainfall, they dry up during the summer, usually during the early to middle summer, for they are not fed by any springs or aquifers and, furthermore, due to the fact that they flow over the Upper Cretaceous limestones, some of their water percolates downards. The individual subcatchments drained by them cover 66, 28 and 23 km^2 respectively, while their total length is 14.5, 12.5 and 17.5 km, again respectively.

Indicative data of the sparse measurements of their discharge rate, taken during the period 1963-67, are noted below. For the Lagadas tributary, the highest discharge-rate values recorded were 2.363 m^3/sec (26 December 1963) and 1.0 m^3/sec (3 December 1963), while its general winter peak run-off ranged between 0.2 and 0.6 m^3/sec.

For the Lapatou tributary, the highest discharge-rate values were recorded as being 2.0 m^3/sec (16 April 1965) and 1.320 m^3/sec (26 December 1963), while its general winter peak run-off was of the order of 0.2-0.3 m^3/sec. For the Sfikas tributary, the highest values recorded were 0.815 m^3/sec (20 November 1963) and 0.780 m^3/sec (20 January 1965), while its winter discharge rate ranged between 0.05 and 0.2 m^3/sec.

Finally, the Zarzakis tributary, flowing just to the south-east of the town of Megalopolis, is also a winter stream. It drains a subcatchment of just 22 km^2. The highest discharge rate recorded was 1.845 m^3/sec (16 February 1965), while its general winter peak run-off ranged between 0.2 and 0.4 m^3/sec during the period 1963-67.

8.5 Hydrological balance of the Alfios river catchment

The groundwater budget for each hydrological catchment unit may be expressed in terms of a general balance equation of the form:

<u>Inflow</u> = <u>Outflow</u> + <u>Changes in storage</u>, where

<u>Inflow</u> represents the amount of water percolating downwards to the groundwater table (eg from infiltrated precipitation or from a river running through the basin) or supplied by underflow from adjacent hydrogeological units.

<u>Outflow</u> represents the amount of water leaving the aquifer discharged by springs, drained naturally (river base-flow) or artifically (via the construction of channels) or lost through evapotranspiration or by abstraction through wells.

<u>Changes in storage</u> are equal to the deficit or the surplus, in relation to the overall budget, in groundwater storage and in the soil moisture content.

The hydrology of the groundwater (groundwater budget of the catchment) is closely related to that of the surface water, the two being interdependent to a certain extent.

The surface water budget for each hydrological catchment unit may also be expressed in terms of a general balance equation of the form:

$$P = E + R + I, \text{ where}$$

P = the amount of water precipitating over the catchment,

E = the amount of water lost through actual evapotranspiration,

R = the total run-off (surface run-off, interflow, base-flow) from that catchment and also underflow (flow at depth through the aquifer) and

I = the amount of water infiltrating downwards either to the water table or to make up any previous losses in the soil moisture content.

Here must to be pointed out the possible double character of a river or a stream which may be either influent to or effluent from the aquifer, depending on the season.

The calculation of the hydrological balance of a catchment by estimating the individual parameters presents many problems, especially given the limited amount, or even lack, of information available.

Values of actual evapotranspiration are not available for the study area and so evapotranspiration either remains as an unknown factor in the calculation of the hydrological balance and is assumed to make up the balance required by the other values or is indirectly calculated from various developed formulae (Section 7.3). Similarly, the amount of water percolating downwards to the water table, ie the infiltration or inflow factor, can be taken to equal the amount of groundwater discharged from the aquifer (eg through springs or natural drainage) and making up the base-flow of the river (which can be obtained from the river hydrographs), as changes in the groundwater storage and soil moisture are usually considered to be small and may effectively be ignored when working on a water year basis.

When all these broad assumptions are made, it is usually possible to produce a water balance the limitations of which must, however, be realised.

A problem often arises here in determining the limit of the groundwater catchment. This can differ considerably from the surface water catchment and therefore any attempt to calculate a balance for the groundwater based on the surface water catchment might well lead to incorrect results being obtained.

It was not possible to calculate the hydrological balance of the Alfios catchment during the present study due to the complications in evaluating its various components for which insufficient data were available. The main problem was in establishing the exact extent of the groundwater catchment, made even more difficult by the large size of this catchment.

The Alfios river catchment is underlain by the geological formations of the Pindos zone, the Tripolis zone, together with its basement, and the Phyllitic-Quartzitic series, while the Neogene basins of Megalopolis and Assea are filled with unconsolidated sediments.

The highly permeable Upper Cretaceous limestones of the Pindos zone, occurring either in the form of successive thrust-slices, as on the western side of the catchment, or as independent nappes, as on the southern and eastern sides of the catchment, form aquifers which either discharge through springs of small, medium or even large size within the catchment or which are, in places, in hydrological continuity with the underlying carbonate rocks of the Tripolis zone.

The carbonate rocks of the Tripolis zone and the overlying limestones of the Pindos zone, which are in hydrological continuity with them, cover a great area of the catchment, estimated at roughly 30-35%.

The carbonate rocks of the Tripolis zone (approximate thickness 1000 m) which are also highly permeable, form vast, extensive aquifers, discharged through large springs situated outside the Alfios catchment, such as the Lousios river springs and probably also the Aghios Floros and Pidima springs. The direction of flow of the groundwater is determined by the subsurface morphology of the impermeable underlying formations, ie the Tripolis low-grade metamorphic basement and the Phyllitic-Quartzitic series of rocks.

The Lousios river springs are situated to the north-west of the Alfios river catchment (at an elevation of about 420-430 m) along the bottom of the Lousios river valley which is incised within the carbonate rocks of the Tripolis zone (Plate 4a). This group of springs is of overflow type, with the overlying flysch acting as a barrier (Fig 3.2). No direct gauging data of their discharge are available. However, some data (mean daily discharge for the period 1958-61) do exist for the Lousios river from a gauging station situated a few hundred metres downstream from these springs (Table 8.7). The base-flow of the Lousios river, especially during summer, originates predominantly (estimated at 60-70%) from this group of springs.

Year/Month	April	May	June	July	Aug	Sept	Oct	Nov
1958	7.57	6.04	5.12	4.47	4.22	4.22	4.22	4.22
1959	7.82	7.14	6.75	6.24	5.70	5.48	5.45	7.12
1960	10.08	5.64	4.71	4.07	3.85	3.98	3.85	3.85
1961	7.02	6.27	5.24	4.99	4.80	4.59	4.63	5.02

Table 8.7 Mean monthly discharge (in m^3/sec) of the Lousios river at the bridge of Kokori (1958-1961).

The Aghios Floros group of springs is situated a few kilometres to the south-west of the Alfios catchment, more or less at the junction of the carbonate rocks of the Tripolis zone with the alluvium deposits filling the Kalamata basin. The springs flow at an elevation of 40 m and their total discharge averages between 6.0 m^3/sec (end of February) and 4.0 m^3/sec (end of September). The spring of Pidima is situated a few kilometres south of the Aghios Floros spring, again at the contact between the carbonate rocks of the Tripolis zone and the alluvium deposits filling the Kalamata basin. Its discharge averages between 1.5 m^3/sec (end of February) and 0.2-0.3 m^3/sec (end of September). (Data for the period 1962-63 from the Gold Report, 1963.)

It is possible that the carbonate rocks of the Tripolis zone and the hydrologically adjacent Upper Cretaceous limestones of the study area drain in the same direction as the large Tripolis basin (almost 50 km long and less than 15 km wide) which is totally enclosed by a rim of surrounding limestone mountains and is situated at an elevation of between 600 and 700 m. It drains through sink holes (katavothres) which are probably in hydrological continuity with some or all of the four major groups of springs of high discharge emerging on the northwestern and western sides of the bay of Argos in the eastern Peloponnese. They issue more or less at the contact of the Tripolis carbonate rocks and the alluvium deposits of the plain of Argos or close to the contact of the carbonate rocks with the sea. From north to south, they are the Kephalari spring of Argos, the Lerni group of springs at Myloi, the Aghios Georgios spring on the coast, a submarine spring south of Kiveri and the great Anavolos submarine spring at Astros.

A project using tracers (tritium, fluorescine), carried out during 1961 and 1962 and funded by the F.A.O. (Food and Agricultural Organisation) of the United Nations, proved the existence of a hydrological continuity between the sink hole (Katavothra) at Nestani (14 km NE of the town of Tripolis) and the Aghios Georgios spring at Kiveri (travel distance 27 km) and also between the 'katavothra' at Partheni (13 km ESE of the town of Tripolis) and a karstic spring situated 4 km further east.

This in fact highlights a great problem concerning the direction of drainage of the water of the carbonate rocks of the central-eastern Peloponnese and also of that water sinking into the swallow holes in these areas, but its discussion and the determination of the possible points of discharge are beyond the purposes of the study undertaken here. A project undertaken by IGME using tracing and also other techniques is, in fact, at present in operation, seeking to solve the above major hydrological problems, ie to determine the direction of drainage of the Tripolis zone carbonate rocks, the direction and the point of discharge of the water flowing into sink holes, a great number of which exist along the eastern margin of the high plateau of Tripolis, and also of the surplus water of the small lakes of Stymphalia and Taka which also discharge through 'katavothres'.

Given the difficulties encountered, arising from the fact that the carbonate rocks of the Tripolis zone and those limestones of the Pindos zone which are in hydraulic continuity with them both discharge outside the drainage basin of the Alfios river, even a rough calculation of the hydrological balance of the Alfios river catchment proves impossible, unless certain data are provided, these being the exact extent of the area occupied by the carbonate rocks of the Tripolis zone and the hydraulically adjacent limestone of the Pindos zone and also the accurate infiltration rates of these formations.

If the extent of those areas covered by the formations referred to above is excluded from the calculation, then the amount of direct run-off of the streams originating from these areas and contributing to the run-off of the Alfios river must be subtracted from the balance. Unfortunately, data concerning their flow are not available.

On the other hand, if the extent of the underground catchment were taken to coincide with that of the surface water, then calculations for obtaining a balance for the basin would be inaccurate, unless the exact extent of the carbonate rocks of the Tripolis zone and the hydraulically associated limestone of the Pindos zone and also their accurate infiltration rates were taken into account, in order to allow the calculation of the amount of water leaving the basin.

An approximate rough balance in which calculations were based on such generalisations regarding the situation and on assumptions (referred to at the beginning of the section) would, due to the large size of the Alfios river basin, be totally unrealiable and was not, therefore, undertaken.

8.6 Conclusions

The wider area of the Megalopolis basin is drained by the Alfios and its tributaries of which the main ones are the Xerilas, Elisson, Lagadas, Kastritis and Valtos Choremiou. The Alfios catchment presents a relatively high relief, most of it being mountainous.

1) The Alfios river and its catchment were assigned to Order 6 according to Strahler's method of classification (1954a) while its main tributaries were assigned to Orders 5 to 3.

2) The degree of development of the drainage system depends on a number of factors, such as the lithology and permeability of the bedrock, the presence of certain structures and also on the relief of the catchment and the amount of annual precipitation. A sparse drainage system has developed in the areas where highly permeable rocks outcrop (ie carbonate rocks, Upper Createaceous limestones) while a dense drainage system is present in those areas where rocks of low permeability occur (ie metamorphic rocks, first flysch and flysch).

   Examination of the drainage patterns reveals that structure and especially faulting have had a profound effect on their development. In general, the Alfios drainage system can be considered as showing a centripetal pattern, although on a regional scale rectangular, parallel and dendritic patterns of development are clearly distinguished.

3) The average total mean annual rainfall over the Alfios catchment (1962-77) was calculated, by applying three different methods of calculation, at 967.8 x 10^6 m^3/year.

4) An effective infiltration coefficient (Ie) of 55% was calculated for the Upper Cretaceous limestones of the Pindos zone by using a direct method and applying it to the total yield of the Palataki spring.

5) The coefficient of the total run-off of the Alfios was calculated as 27% of the total precipitation (mean value for 8 years covering the period 1962-75). This relatively low value is attributed to the relatively high evapotranspiration in the catchment (68% at the Megalopolis station) and also to the fact that the groundwater of the carbonate rocks of the Tripolis zone discharges outside the Alfios catchment and does not, therefore, contribute to the Alfios base-flow.

6) The Alfios is predominantly a winter river. It dries up, upstream from the Kyparissia bridge, during relatively dry years. At the Karytena bridge, at the northern end of the basin, it always has a substantial base-flow, the lowest values being between 0.4 and 0.1 m^3/sec (1962-76). The water originates from karstic springs, overflow of the karstic aquifers and groundwater retained in the terraces.

7) A figure of 4.8 days was calculated for the Alfios catchment as the interval of time after which the bulk amount of direct run-off had been discharged.

8) The recession period for the Alfios, during which all or almost all of its water originates from groundwater discharge, generally lasts from April to November, a mean figure of 209 days having been calculated.

9) At least two recession constants for the Alfios can be calculated for successive periods of the recession. This indicates a

continuously changing set of hydrogeological conditions. A higher recession constant of 0.0091 was calculated for the first part of the recession period (usually from April to July) when most of the water is derived from the karstic aquifers and also from bank storage and a lower recession constant of approximately 0.003 was calculated for the rest of the recession period when most of the water is thought to derive from the lowly permeable, unconsolidated basin sediments.

10) Most of the main tributaries of the Alfios carry a low amount of base-flow during summer, the water originating from karstic springs or groundwater retained in the terraces. A few others (eg Lagads, Lapatou and Sfikas) dry up in the early summer.
A great part of the flow of the Elisson and Xerilas streams, major tributaries of the Alfios, percolates into the carbonate rocks of the Tripolis zone along the areas where they flow over these rocks.

11) Despite certain broad generalisations and assumptions which can be made in cases where inadequate data are available, it proved impossible to formulate even a rough calculation of the hydrological balance of the Alfios catchment. This was due to the problems encountered in determining the extent of the groundwater catchment which, in the case of the Alfios river, differs considerably from the surface water catchment. This is due to the fact that the carbonate rocks of the Tripolis zone, together with part of the Upper Cretaceous limestones, the two being in hydraulic continuity and covering an area roughly estimated at 30-35% of the catchment, discharge outside the Alfios catchment. If further assumptions were introduced to the calculations, the results would, due to the large size of the catchment, be totally unreliable.

PART III HYDROGEOLOGY

CHAPTER 9: HYDROSTRATIGRAPHY

9.1 Introduction

A hydrogeological map of the study area on a scale of 1:100,000 has been prepared (Fig 9.1) following the instructions and guidelines set out in the International Legend for Hydrological Maps (Unesco 1983).

On this basis, the geological formations were divided into five groups based on their bulk permeability and also on the type of porosity and the resulting nature of the groundwater movement that takes place within the rocks (eg porous or fissured (karstic) rocks).

The first two groups were categorised according to the degree of permeability among the porous rocks (ie the formations filling the basin) dividing them into high or low to moderately productive aquifers (aquitards). The third group includes the highly permeable karstic formations of the area. Finally, the last two groups include both porous and fissured rocks. The fourth describes formations where only minor aquifers, usually of local extent, or minor discontinuous aquifers are developed, while the fifth includes the practically non-aquiferous formations (aquicludes).

Assessments of the degree of permeability of the various geological formations in the area were based on hydrogeological field observations. Lithological constitution was the primary consideration, although the presence and size of springs originating from the various formations, as well as the presence and productivity of wells drilled in them to provide water supply and irrigation, were also examined.

A more detailed description of the hydrogeological status of the various formations occurring in the area, together with a table (9.1) listing the geological and hydrological features of each formation, is given in the following Section (9.2).

The direction of the groundwater movement within the karstic outcrops is also indicated on the hydrogeological map. The direction of groundwater movement in the Upper Cretaceous limestones in the western, north-western and northern parts of the basin generally takes place in a S-N or N-S direction, as a result of the regional structure. The groundwater of the limestone part of each thrust-slice discharges through the nearest karstic spring located at the lowest point of each of the individual limestone outcrops. It was not possible during the present study to determine the direction of groundwater movement within the carbonate rocks of the Tripolis zone in the north-eastern and northern parts of the area nor within those outcrops of the Upper Cretaceous limestone which are in hydraulic continuity with the carbonate rocks of the Tripolis zone. The direction of movement of groundwater in these areas as shown on the map is only an approximation, since it is, for most of the area, based on insufficient hydrogeological data.

The springs located on this map, most of which are karstic, were divided into two categories according to their mean discharge, based either on available data or using a rough visual estimate of their discharge during the summers of 1982-85 when field work was carried out. The first category comprises springs with an average discharge lower than 100 l/sec, while the second one includes those with an average discharge greater than 100 l/sec. It should be noted that the size of the springs within each category ranges greatly, eg the springs situated at the bottom of the Lousios valley and which have a lower discharge during the late summer of approximately 4 m^3/sec are included in the second category even though their flow is appreciably higher than the 100 l/sec required to belong to this category.

Please see corresponding map in the

pocket of Volume I

Fig 9.1 Hydrogeological map of the area (Tsiftsis 1987).

A detailed reference to the discharge of the springs located in the northern part of the Megalopolis basin is given in Section 10.

The form (as at November 1980) of the piezometric contours of the karstic aquifers developed in the vicinity of the Kyparissia field is also shown on this map .

It should be noted that only a few geological features, such as overthrusts and main faults, or topographic features, such as villages and main roads, have been indicated on this map.

For a complete geological identification of the various hydrological units distinguished on this map, it should be viewed in conjunction with the geological map on a scale of 1:25,000 to be found in the pocket of Volume I.

9.2 Hydrolithological description of the geological formations occurring in the study area

In this chapter, the degree and type of permeability of each formation and of the carbonates in particular (ie the Upper Cretaceous limestones and the carbonate rocks of the Tripolis zone) is described.

The rocks making up the basin and its margins can be divided into two broad categories.

The first comprises the unconsolidated deposits filling the basin. Here, the permeability varies greatly from one formation to another and also, in many cases, even within a formation (porous media). The second group includes the alpine and pre-alpine formations of both the Pindos and Tripolis zones and the Phyllitic-Quartzitic series which are, in turn, subdivided into two further categories: 1) the highly permeable carbonate rocks of both zones, the permeability of the carbonate rocks

System Period	Series Stage	Group (Geotectonic Zone)	Formation-Unit	General Lithology	Thickness (in m)	Hydrogeological Status (features, characteristics)
Quaternary	Holocene	Basin formations	River gravel fills	Unconsolidated clays, sands, rounded pebbles	few	Major aquifer
			Alluvium	Sand-clayey materials with dispersed pebbles	few	Aquifer - minor aquifer locally
			Scree and talus cone	Unconsolidated to slightly cohesive, of limestone gravels and clays	few	Major aquifer - aquifer locally only
			Terraces: Lower	Unconsolidated gravels, sands and clays with rounded pebbles usually small in size (up to 10 cm)	5	Major aquifer
	Pleistocene		Terraces: Middle or Thoknia	Composed of a lower part of loose to slightly consolid-ated coarse-grained gravels, sands and clays and an upper-flood plain of sands and clays	5-10	Major aquifer - aquifer
			Terraces: Upper or Potamia	Slightly consolidated gravels, sands and clays; pebbles are rounded or angular and of various origins. Pebble increases size towards the margins of the basin	5-10	Aquifer - minor aquifer locally
			Terraces: Lousios	Loose to medium cohesive gravels with sands and clays. The sandstone fragments have in places undergone significant alteration	10-15	Aquifer - minor aquifer locally
			Choremi Stage: Megalopolis beds	Fluvial deposits of clays, sands and gravels orloosely cemented conglomerates (centre area) and of sands and clays mixed with pebbles and partly of gravels (margins)	>50	Minor aquifer
			Choremi Stage: Marathousa beds	Lacustrine beds of alternations of marls, clays, humus clays and lignite (centre area). Fluvial deposits of clays, sands and gravels or loosely cemented conglomerates (margins)	±200	Aquiclude - minor aquifer locally
			Apiditsa Stage	Alternations and lateral transitions of clays, sandy-clayey beds with loose to slighly cohesive breccio conglomerates with sands and clays	60-80	Aquiclude - minor aquifer locally
			Assea basin deposits	Alternations of clays and sands with dispersed pebbles and lenticular concentrations of sand and gravels to slightly consolidated breccio-conglomerates	10-30	Aquifer - minor aquifer locally
Tertiary	Upper Pliocene		Trilofon Stage	Partly lacustrine clays, marls and thin inter-calations of slightly cemented conglomerates and partly fluvial deposits of gravels, sands, clays and partly cohesive breccio-conglomerates	100-120	Aquiclude - aquifer locally
			Makrysion Stage	Lacustrine marls with thin intercalations (0.2- 1 m) of lignite beds. At its base, a conglomerate occurs	40-100	Aquiclude
U. Mesozoic - L. Tertiary	Upper Maestrichtian -Palaeocene	Pindos zone	Transition beds	Thin-platey alternations of limestones, black cherts, marls and sandy marls	5-100	Aquifer
	Turonian-Maestrichtian		Upper Cretaceous limestone	Thin to medium bedded, bright-coloured micritic bio-micritic limestones. Sometimes with marly intercalations in the middle and lenses or nodules of chert in the lower and upper members	150-200	Major aquifer
	Lower Cretaceous-Turonian		First flysch	Mainly medium-grained sandstones	150-200	Aquiclude
	-	'Tectonic block' formation	'Tectonic block' formation	A "mélange" of sandstones, cherts, igneous rocks, breccio-conglomerate particles and limestone blocks of the Pindos and Tripolis zones	0-200	Aquiclude: Its varying thickness does not affect the vertical groundwater movement
U. Palaeozoic - L. Tertiary	Upper Eocene-Oligocene	Tripolis zone	Flysch	Alternations of sandstone, clay and pelite beds	±500	Aquiclude
	Upper Triassic-Eocene		Carbonate rocks	Thick-bedded to massive dark-coloured limestones and dolomites	<1000	Major aquifer
	Upper Palaeozoic-Lower Triassic		Low-grade metamorphic basement (Tyros beds)	Crystalline limestone-dolomites, phyllites	visible 80-100	Aquiclude
	?	P-Q Series	Phyllitic-Quartzitic series	Schists-quartzites	visible >700	Aquiclude

---- unconformity
++++ thrust

Table 8.1 Hydrostratigraphic table

being heterogeneous and secondarily developed (karstified rocks), and 2) the rest, which are impermeable formations.

The alluvium deposits, consisting generally of sandy-clayey materials with dispersed pebbles and gravels, are only permeable to a certain extent as the high proportion of clay and clayey materials contained within them results in a locally low degree of permeability. Aquifers developed in a few places within them are generally of low to medium productivity.

The talus cones consisting of limestone gravels and clays always have a high degree of permeability, while the scree formations of a similar lithology are somewhat less permeable due to the greater proportion of clays in their constitution. As these formations are formed almost directly on the highly permeable carbonate rocks, aquifers are not developed within them as water percolates downwards to the lower strata.

The terrace gravel-bodies related to the river system and consisting of unconsolidated to slightly cohesive (the older ones) gravels with clasts of various sizes and origins, sands and clays are, in general, of good permeability. However, the greater proportion of clay, originating from the decomposition of the sandstone fragments, noticed in the older terrace bodies (the Potamia and Lousios ones), reduces their permeability markedly. The irregular lithological composition of the terrace gravel-bodies, resulting from the manner of their deposition, implies that local differences in permeability distribution should exist within them and that channels or lenses of higher permeability than the rest of the bodies must occur.

The Megalopolis beds of fluvial origin, consisting of unsorted clays, silts, sands, gravels or slightly cemented conglomerates in the centre of the basin or of sands and clays mixed with pebbles and partly of gravels at its margins, are generally deposits of low permeability and only locally, towards the margins of the basin, does a better permeability exist. Wells sunk into them for water supply for domestic use or for irrigation purposes are of low to medium productivity.

The lacustrine Marathousa beds of marls, clays and lignite are overall an aquiclude formation. Only minor aquifers of local extent are developed in the lower parts of the formation where thin layers or lenses of sand or coarser material occur. Parts of the lignite beds, where they are fragmentary and fissured, are also relatively permeable with minor aquifers developed in them. In places, they are in hydraulic continuity with the karstic aquifers as, for example, in part of the Kyparissia field. The fluvial deposits of the Marathousa beds, made up of clays, sands and gravels or slightly cemented conglomerates, are generally of low permeability and again only minor aquifers are to be found in them.

The Apiditsa beds, consisting of alternations and lateral transitions of clays, sandy-clayey units and gravels to slightly cohesive conglomerates, are also an aquiclude formation overall, although minor aquifers of restricted extent are developed in layers or lenticular beds of gravels and sands.

The lacustrine deposits of the Trilofon stage of clays, marls and thin intercalations of loosely cemented conglomerates are also aquicludes. However, in parts of the fluvial facies deposits of the Trilofon stage of gravels and aggregates of sands, clays and partly cohesive conglomerates, a better permeability exists and minor aquifers occur.

The Makrysion stage formation, consisting mainly of marls, is a totally impermeable formation.

Finally, the Pleistocene deposits of the basin of Assea, consisting of clays and sands with dispersed pebbles or lenticular concentrations of sand or gravels to loosely cohesive conglomerates, present a varying degree of permeability characterised as an aquifer exhibiting medium productivity.

It should be understood that the variations in the lithological composition of most of the geological formations filling the basin of Megalopolis result in a widely differing permeability distribution, even on a local scale. The percentage of clay minerals present plays an important role in determining the degree of permeability.

Masch and Denny (1966) studied relationships between permeability and the statistical parameters that describe the grain size distribution of a porous medium, such as the average size, dispersion, skewness, peakedness and modality of the distribution. On an experimental basis they evaluated and presented graphically, via a set of predictive curves, the permeability of an aquifer sample in relation to its measured parameters, namely the average size and dispersion, and found that these two parameters best described the relationship between permeability values and the grain size properties of the porous medium. They concluded that permeability values increase with increasing particle size values (ie of Md50 diameter).

Porosity in carbonate rocks results from many processes, both depositional and post-depositional, the latter exerting the most fundamental control. Unlike aquifers in porous, non-soluble rocks in which permeability tends to be an inherent quality, the permeability of aquifers in carbonate rocks tends to develop mainly through the circulation of water and solution of the rock (karstification), resulting in an uneven local distribution of permeability.

Karstification occurs as a result of the solution of the carbonate rocks, near to the surface, by water which flows through them. The rate of solution is influenced primarily by the amount of water circulating and its dissolved carbon-dioxide content and also, to a certain extent, by the composition of the carbonate rocks themselves (see also Hydrochemistry Chapter (13)).

The circulation of water and solution activity tends to be greater in the upper part of the zone of saturation and lessens with increasing depth. With the passing of geological time, the depth of karstification increases until it reaches a 'base level', namely that of the sea-controlled base saturation level or the surface of contact with the underlying impermeable formation.

Burdon (1965) noticed that both solution and enlargement of fracture-openings by the circulation of water follow two dominant directions, ie vertical above the surface of saturation and sub-horizontal on and just below it. There are marked differences between zones of saturation upheld by impermeable formations and those lying above the sea-controlled base saturation level. Quaternary variations in the relative levels of land and sea have resulted in several karstified horizons in and below the coastal areas of Greece.

When the circulating water becomes oversaturated in dissolved bicarbonate, precipitation of the carbonate may, under certain conditions, take place, resulting in the formation of calcite, sometimes in well-formed crystals filling the fissures, most frequently those lying below the water table. At the surface, although terra rossa and other insoluble materials may represent only 2% of the original rock (Burdon, 1965), they nevertheless form an effective infiller of joints and crevices of karstified carbonate outcrops.

Lattman and Parizek (1966), who studied the relationship between fracture traces and the occurrence of groundwater in carbonate rocks, found that the fracture traces and other topographic irregularities detected on air-photographs in the limestone and dolomite terrains might be a manifestation of fracture zones along which greater weathering and increased solution and hence enlargement of the voids along the individual joints, fractures, faults and bedding planes has taken place, thus giving rise to greater permeability. These zones, therefore, offer the most promising prospecting areas for groundwater investigations.

As has already been noted, the productivity of the carbonate rock aquifers depends largely upon the size, number and interconnection of the water yielding joints, fissures and solution cavities, the enlargement of which increases with greater movement of groundwater. The factors responsible for the development of this type of porosity distribution include bedding planes, joints, variations in rock type and texture and also the degree of primary porosity.

The conduits through which the groundwater circulates in the carbonate rocks of Greece are the widespread joint systems and localised fissures induced by the compressive forces of the Alpine Orogeny and the faults resulting from the subsequent tectonic relaxation (Burdon, 1965).

The carbonate rocks of the Tripolis zone are karstified to a very high degree. This is due to the nature of these carbonate rocks as thick-bedded to massive, neritic, usually with a saccharoidal texture, pure carbonates, and also to the jointing and faulting developed during the emplacement of the Tripolis zone, a nappe of the Peloponnese nappe sequence.

Dolomites are more resistant to karstification than are limestones. In the field, the dolomitic layers often protrude above the limestone ones. Weyl (1960) reported that, in sub-surface waters containing relatively low concentrations of total CO_2, dolomitisation will take place by mole-for-mole replacement of calcium by magnesium, without macro-transport of carbonate. Initially, dolomitisation of a lime mud will tend to reduce the porosity and permeability of the rock but, if this process continues beyond a certain stage (ie that of dolomite comprising more than 55% of the rock volume), it will lead to an increase in the porosity and to a marked increase in the primary permeability, as the dolomite crystals are larger than the lime particles.

A fully developed karst topography can be observed in the northern and north-eastern parts of the area, where extensive outcrops of the carbonate rocks of the Tripolis zone occur. Various karstic forms were observed in this area including small poljes, a few dolines and elongated steep, dry valleys, the latter often developed along major fault zones.

A porosity of a rather coarse texture can be identified in the carbonate rocks of the Tripolis zone. This cavernous type of porosity implies the presence of a dense, well-developed, interconnected system of caverns, channels, pipes and conduits irregularly developed along fractures, fissures, joints and bedding planes and, in particular, at the intersection of two or more of these features, the whole system having been largely modified by solution. At present, a few of the fractures and joints can be seen to extend to a relatively great depth below the surface, while a few others are filled with terra rossa or, less often, with secondarily-formed calcite.

The presence of closed drainage basins drained by sink holes, together with the scarcity of perennial streams in these areas, indicates the development of this coarse texture of porosity in the carbonate rocks of the Tripolis zone and hence of a conduit type of groundwater movement.

Furthermore, the size of the springs through which they discharge and which are located outside the Megalopolis basin (see Section 8.5) gives an idea of the degree of karstification they have undergone.

The karstification of parts of the carbonate rocks of the Tripolis zone may have started during an early tectonic stage in the Lower to Middle Eocene, when parts of this zone were uplifted and exposed to erosion. Subsequent to the overthrust of the Tripolis zone during the Oligocene - Miocene, karstification began in those places where the overlying flysch formation had been eroded.

The Upper Cretaceous limestones of the Pindos zone are also highly karstified, although a different degree of karstification from that developed in the carbonate rocks of the Tripolis zone is recognised. This is due mainly to their nature as thin to medium-bedded, micritic, pelagic limestones and also to their generally low content of clay minerals. The presence of intercalations or lenses of cherty or pelitic beds considerably restricts the degree of karstification, although the intense tectonic deformation of these limestones during the overthrust processes and the subsequent relaxation stage did, on the contrary, create conditions favourable to intensive karstification.

The transition beds to the flysch of thin-bedded to platey alternations of micritic limestone, marly limestone, marls and cherts are karstified to a much lesser extent.

The relief of the areas covered by the Upper Cretaceous limestones is, generally, much gentler than the relief of those covered by the carbonate rocks of the Tripolis zone, as the karst topography is not fully developed for the reasons given above. Typically karstic forms are not very often observed. A few small caves and, in a few places, small subsidences considered to be of karstic origin were seen. The bottom of these subsidences is covered by terra rossa and gravel formations.

At the outcrops of the Upper Cretaceous limestones around the villages of Zoni and Palamari, where drainage takes place through sink holes, a cavernous type of porosity is present, consisting of small caves, channels and elongated openings, known by the presence of air currents to be interconnected.

Two types of texture of the secondary porosity developed as a result of karstification in the Upper Cretaceous limestones can be distinguished, these being a fine and even texture and a coarse and uneven one. The first type is of minor porosity in the form of fractures, joints and bedding planes partly modified by solution. The groundwater movement is characterised in this case as diffuse flow. The second type, less developed here, consists of a well integrated system of caverns, pipes and conduits. The type of groundwater movement here is characterised as conduit flow.

In places where the Upper Cretaceous limestone texture was partly or completely destroyed, resulting in the formation of a type of breccio-conglomerate, in places only loosely cemented, the karstification was less intensive, despite the fact that rapid circulation of water takes place through the voids between the rock fragments.

The exact depth reached by the karstification processes is not always known. Given the long period over which it has been taking place and also the intensity of the tectonic deformation of the Upper Cretaceous limestones, it is considered that, in most cases, karstification must by now have reached the surface of the contact with the underlying impermeable formation, ie the first flysch of the Pindos zone on the western side of the basin and the flysch formation of the Tripolis zone on its eastern side.

The presence of a great number of karstic springs, originating from the Upper Cretaceous limestone outcrops, with a comparatively high discharge related to the size of the limestone masses feeding them, is evidence of the relatively high degree of karstification here.

The beginning of the karstification processes in the Upper Cretaceous limestone coincided with that stage of the Pindos zone tectonic evolution at which it was displaced, elevated above sea-level and overthrust onto the Tripolis zone in the Upper Oligocene/Lower Miocene.

The Upper Cretaceous limestones are covered in most places in the Megalopolis basin by younger, relatively impermeable formations and must now lie below the groundwater and surface water circulation systems, as they are not in hydraulic continuity with the overlying aquifers or river network. In these cases, permeability inherited from the earlier periods of karstification should exist (Legrand and Stringfield, 1971).

In the Kyparissia field, where parts of the Upper Cretaceous limestone protrude through the basin sediments and are even, in a few places, in hydraulic continuity with the surface water of the Alfios river, a lateral development of the karstification may be assumed to have continued in places where they are buried beneath the impermeable basin sediments.

CHAPTER 10: GROUNDWATER OCCURRENCE IN THE BASIN OF MEGALOPOLIS - CONTRIBUTION TO THE KYPARISSIA FIELD

10.1 Introduction

The main karstic aquifers occurring in the wider area of the basin of Megalopolis are, as has already been stated in the previous chapter, the Upper Cretaceous limestones of the Pindos zone and the carbonate rocks of the Tripolis zone.

A great part of the area is built up of Upper Cretaceous limestones - a major aquifer - which either overlie the first flysch of the Pindos zone or are, in places, overthrust onto the flysch of the Tripolis zone, both of the latter being impermeable formations. This complex structure has led to the development of several individual karstic aquifers in and around the basin of Megalopolis.

On the western side of the basin, the Upper Cretaceous limestones partly make up a number of thrust-slices which form the structural setting here and give rise to the development of a number of individual karstic aquifers, discharging through karstic springs located on this side of the basin.

On the northern and north-eastern sides of the basin, the hydrological regime resulting from the structure of the area is rather complicated. Part of the water of the Upper Cretaceous limestones discharges through a small number of karstic springs situated in the northern part of the basin of Megalopolis, while the rest percolates downwards to a lower karstic aquifer system developed in the carbonate rocks of the Tripolis zone.

Finally, on the eastern and south-eastern sides of the basin, the separate parts of the Pindic nappe, overthrust onto the non-permeable flysch of the Tripolis zone, discharge through individual springs.

The carbonate rocks of the Tripolis zone outcrop around the northern, eastern and southern sides of the basin and form an aquifer system deeper than that developed in the Upper Cretaceous limestones of the Pindos zone.

This lower aquifer system is discharged through a small number of high discharge springs, eg those springs (coastal and submarine) situated around the town of Argos and also the springs of Aghios Floros and Pidima, to the north-north-west of the town of Kalamata, both areas being located far away from the basin of Megalopolis (see map of Fig 1.1). Part of the carbonate rocks of the study area must discharge through the high discharge springs situated in the bottom of the Lousios river valley, to the north of the basin. Only one small spring issues from the carbonate rocks of the Tripolis zone. It is located 300 m west-south-west of the village of Karatoulas at the contact between the carbonate rocks of the Tripolis zone and the Tyros beds.

The direction of movement of the groundwater on a regional scale within the carbonate rocks of the Tripolis zone is controlled by the structure (sub-surface development and distribution) of the non-permeable formations, ie the low-grade metamorphic basement (Tyros beds) and the Phyllitic-Quartzitic series in cases where the carbonate rocks are directly overthrust onto it.

The study of the hydrology of the carbonate rocks of the Tripolis zone was deemed to be beyond the purposes of the present study, for the aquifer developed in the carbonate rocks does not affect the regional hydrogeology of the Kyparissia field, due to the fact that a thick horizon of flysch of the Tripolis zone lies between them. Furthermore, this is the subject of a project currently being carried out by IGME.

The positions of the springs occurring in the northern part of the Megalopolis basin are shown on the map of Figure 10.1. They are either contact springs, flowing at the contact between the Upper Cretaceous limestones and the underlying flysch, or overflow springs, located at the contact between the Upper Cretaceous limestones and the first flysch, where the latter is thrust onto the former. The second type of springs also occurs in a few cases at the contact of the limestone with the superficial sediments within the basin. Finally, the springs situated in the Lousios river valley are of the overflow type.

The springs indicated on the map of Fig 9.1 were divided into two categories, according to their mean discharge rate based, in most cases, on a rough visual estimate made in the field during the fieldwork carried out in the summers of 1982-85. Springs with an estimated mean discharge lower than 100 l/sec were assigned to the first category (small springs), while those with an estimated mean discharge higher than 100 l/sec were assigned to the second category (large springs). According to the scheme of Meinzer (in Todd, 1980), these springs are of the 4th to 6th degree of magnitude.

Data concerning the flow rate over a period of six years (1962-67) are only available for those springs situated around and to the north of the Kyparissia field. However, it should be noted here that measurements were taken sporadically and often with long intervals between them.

10.2 Aquifers on the western and north-western sides of the basin

The Pindos zone on this side of the basin consists of a series of thrust-slices (see the geological map (scale 1:25,000) to be found in the pocket of Vol I). The slices are irregular in extent and thickness and

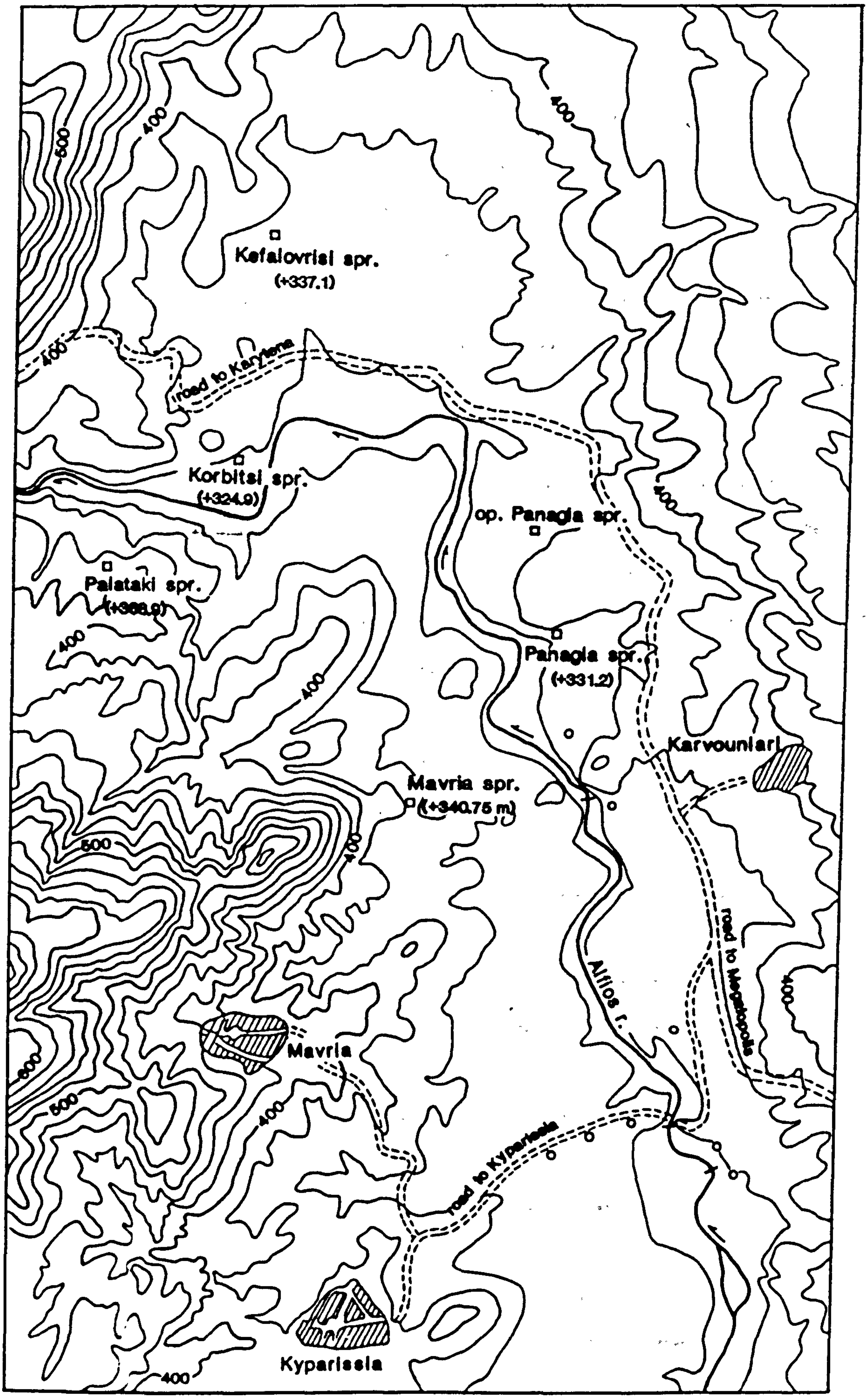


Fig 10.1 Topographical map of the northern part of the Megalopolis basin.

usually comprise a band of Upper Cretaceous limestones, including the transition beds to the flysch and an underlying band of first flysch.

This has led to the formation of several individual karstic bodies discharging through a more or less equivalent number of springs of various sizes, corresponding to the size of the limestone mass which they discharge (see map of Fig 9.1). Furthermore, a few limestone outcrops discharge directly into either the Alfios or the Lousios rivers. The largest of the springs situated on this side occur to the east and north of the village of Kotylion in the north-western part of the basin, around and to the west of the village of Lykosoura and also at the villages of Lykaeon and Kastanochori. Most of the springs occur as contact springs, emerging at the contact between the first flysch and the Upper Cretaceous limestones, although a few overflow springs also occur.

Commonly, the discharge of these springs decreases rapidly in the middle of summer and a few of them, usually those with a relatively small flow, often almost dry up in the late summer to early autumn. This indicates that these springs are of conduit feeder type, ie the circulation of the groundwater takes place through an integrated system of caverns, pipes and channels in the highly karstified limestones.

Data on the discharge of the springs situated on this side of the basin are only available for the spring of Palataki, situated approximately 3 km south-west of the village of Karytena, and the spring of Mavria, situated approximately 3 km north-east of the village of Mavria.

The Palataki spring, which has long been used to supply the village of Karytena with water, discharges a relatively small (approximately 2.75 km^2) limestone outcrop of a thrust-slice extending to its south. It issues at an elevation of 368.9 m and is of overflow type.

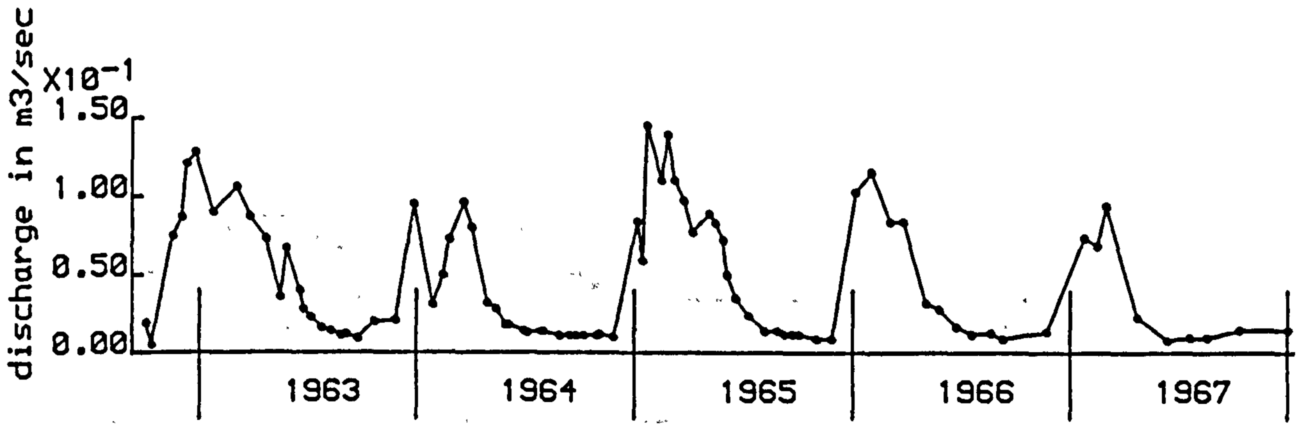


Fig 10.2 Hydrograph of the Palataki spring.

As can be seen from Figure 10.2, the discharge of the Palataki spring increases rapidly after the first autumn rains to more than ten times its steady rate during the dry season when it is about 0.01 m^3/sec. The period during which it undergoes a decrease in flow is relatively short while, for more than half the year, it flows at a steady rate of 0.01 m^3/sec.

According to the local people, an intermittent spring also issues from this outcrop of limestone, flowing only after heavy rainfall. In view of these factors, the infiltration coefficient of 55% calculated using the data of the Palataki spring (Chapter 8.3) should only be used with caution.

The Mavria spring discharges a karstic aquifer of small extent situated on the western side of the Kyparissia field (aquifer No. 6 on Fig 12). Most of this aquifer is covered by the impermeable basin sediments of the Apiditsa stage and it only outcrops in two places, both outcrops being of very small extent.

It flows at an elevation of 340.75 m and has a relatively steady discharge rate of 0.01-0.02 m^3/sec throughout the year (Fig 10.3).

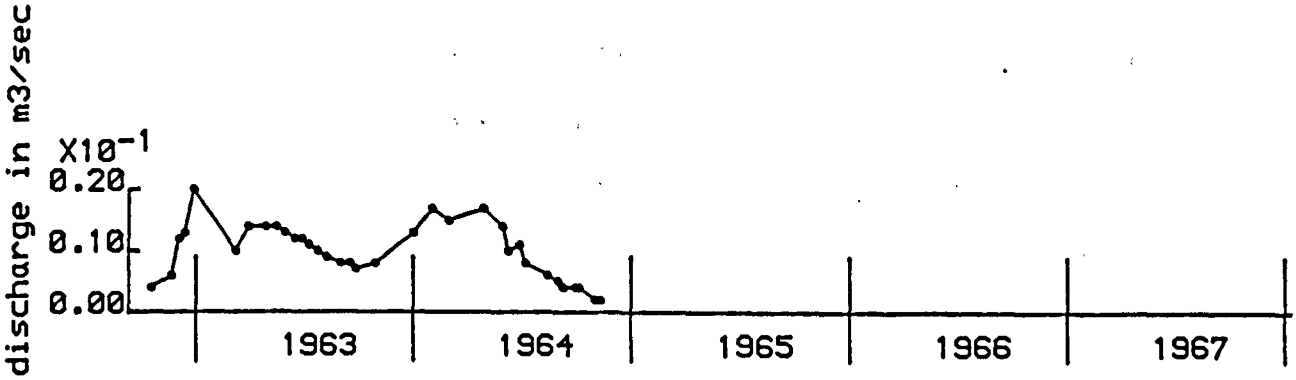


Fig 10.3 Hydrograph of the Mavria spring.

10.3 Aquifers on the south-western, southern and south-eastern sides of the basin

The south-western, southern and south-eastern sides of the basin of Megalopolis were not geologically mapped, for the hydrology of these areas was not believed to be associated with that of the Kyparissia field, ie groundwater is not contributed to the Kyparissia field from these areas. This conclusion was partly based on the rock distribution, as given on the geological map prepared by Lüttig and Vinken (in the Gold Report, 1963), but was mainly based on the experience obtained of the structural-hydrogeological regime of the northern part of the basin when this area was mapped in detail.

A broad hydrogeological reconnaissance of these areas was, nevertheless, carried out in order to determine their hydrogeological regimes.

Thus, in the south-western part of the basin, the same structural pattern was recognised as that occurring along the entire western side of the basin (see Section 4.4.2). The limestone outcrops, parts of the thrust-slices, discharge through individual springs. The largest are the springs which emerge 2 km south-south-east of the village of Ellinitsa and that situated 2 km north-east of the village of Paradisia. Both are of overflow type, emerging at the contact between the Upper Cretaceous limestones and the basin sediments.

In the southern part of the basin, the carbonate rocks of the Tripolis zone outcrop in several places, as to the south and west of the village of Leontarion and also along the entire western side of the village of Ellinitsa (ie on both sides of the Xerilas river valley, which is in fact a graben). The water of the carbonate rocks percolates downwards to the deeper aquifer system developed in the Peloponnese. The water of the carbonate rocks of this area (ie around the Xerilas) probably discharges through the springs of Aghios Floros and Pidima, some 15-20 km to the south-south-west of this area.

In the south-eastern part of the basin, the Pindic nappe is made up exclusively of Upper Cretaceous limestones and generally presents the type of structure occurring on the eastern side of the basin (see Section 4.4.2). The Upper Cretaceous limestones on this side of the basin are to be found overthrust onto the flysch of the Tripolis zone. They, or at least the northern part of their outcrops, discharge towards the Megalopolis basin through karstic springs, the largest of which is situated 1.5 kms west of the village of Voutsaras and flows into the Kutifarena stream, a tributary of the Alfios river.

10.4 Aquifers on the eastern side of the basin

In the eastern part of the basin, two separate outcrops of limestones of the Pindic nappe occur, overthrust onto the flysch of the Tripolis zone.

There are two springs issuing from that part of the Pindic nappe extending west of the village of Marmaria and south of the village of Palaeochouni. The larger emerges at the lowest point of the nappe, in the bottom of the valley which has been cut here by the Alfios stream. This spring is situated 700 m south-west of the village of Papsomatis, less than 100 m outside the mapped area. The smaller, of much lower discharge, flows as a contact spring, issuing approximately 500 metres south-east of the village of Marmaria.

The stratigraphically overturned limestone outcrop of the Pindic nappe, occurring west of the village of Athenaeon, discharges through the spring of Aghios Georgios, which is of overflow type.

The carbonate rocks of the Tripolis zone do outcrop on this side of the basin, although their largest occurrence is in its north-eastern part.

The direction of groundwater movement and the points of discharge of the groundwater of the carbonate rocks percolating down to the deeper aquifer system (ie that developed in the carbonate rocks of the Tripolis zone) cannot be determined from the comparatively limited extent of the study area. It might be possible to determine this movement if the structure of the low-grade metamorphic basement of the Tripolis zone, together with that of the Phyllitic-Quartzitic series (both of them being aquiclude formations controlling the movement of the groundwater within the aquifer in the carbonate rocks), were thoroughly studied. A tracer investigation could contribute greatly towards the solution of this problem.

From the outcrop pattern of the low-grade metamorphic basement of the Tripolis zone and the Phyllitic-Quartzitic series and from the structure of the studied area generally, it may be concluded that the groundwater of at least the greatest part of the carbonate rocks in the study area moves towards and discharges through those springs situated in the Lousios river valley.

These springs are of overflow type, the impermeable flysch of the Tripolis zone acting as water barrier, with a high discharge. Their lowest mean monthly discharge during the period 1958-61 was approximately 4 m^3/sec (see Table 8.7).

10.5 Aquifers on the northern and north-eastern sides of the basin

10.5.1 Introduction - Definition of the extent of the aquifers

The Pindos zone on the northern side of the basin presents an intermediate type of structure between those occurring on the western and the eastern sides (Section 4.4.2). Thus, in an easterly direction, there is a gradual transition from the thrust-slices, usually made up of first flysch and Upper Cretaceous limestones, to a type of nappe, built up almost exclusively of Upper Cretaceous limestones (see also cross-section of Fig 4.6).

The presence of clearly distinguishable thrust-slices extends eastwards as far as the area stretching up to the east bank of the Lousios river. The limestone part of these slices forms an individual aquifer in most cases. The hydrological extent and the point of discharge of each of these aquifers developed to the east of the Lousios river was easily determined.

The strip of first flysch, outcropping to the south and north of the village of Ellinikon and most probably continuing further northwards to connect with the first flysch further to the north of Ellinikon, must define a structural unit and, hence, an individual hydrogeological unit which discharges through the Kefalovrisi and Korbitsi springs, to which reference will be made later (Section 10.5.3).

The bands of the first flysch occurring west and north-west of the village of Stemnitsa also indicate the presence of a few structural and, therefore, also hydrogeological units in this area. That part of the Pindic nappe occurring to the north and west of the village of Stemnitsa in fact discharges through a small number of karstic springs, the positions of which are shown in the map of Figure 9.1. The largest flows approximately 4 km north-west of the village of Stemnitsa and emerges through the 'tectonic block' formation at the base of the Pindic nappe. It supplies water to all of the villages, 14 in total, scattered throughout the eastern part of the Megalopolis basin. Also of relatively high discharge is the spring of Rozena which flows approximately 3 km south-west of the village of Stemnitsa and which supplies the village of Ellinikon with water. All the other springs noticed in the area are of relatively small discharge.

10.5.2 Percolation of groundwater to the deeper aquifer system

Over large areas on the north-eastern side of the Megalopolis basin, the limestones of the Pindos zone are directly overthrust onto the carbonate rocks of the Tripolis zone. An overall non-permeable 'tectonic block' formation is often developed between these two geological units but, due to its generally small thickness (0-30 m) and to its irregular distribution, it does not affect the vertical movement of the groundwater from the limestones of the Pindos zone (upper aquifer) down to the carbonate rocks of the Tripolis zone (deeper aquifer system). The accurate determination of the extent of these areas along which the two aquifers are in hydraulic continuity is not possible. The map of Figure 10.4 shows the probable extent of these areas, based on the interpretation of the general structure of the area as a whole.

Furthermore, subsequent to the overthrust, a faulting stage must have brought these two aquifer systems into hydraulic continuity in places, even in areas where flysch of the Tripolis zone of a relatively small thickness lies between them (eg in places where the throw of the faults is greater than the thickness of the flysch).

The fault, or rather the fault system, running SSE to NNW from east of the village of Ellinikon almost up to the village of Stemnitsa, is the most evident example. This fault zone shows a throw of at least 200-250 m, as is suggested by the steep slope of the topography, the throw being much greater than the thickness of the flysch assumed to be present in this area.

Further examples may be the fault system which runs in a SE to NW direction from the village of Makrysion up to the village of Zoni and also the fault system running in a S to N direction through the village of Karvouniaris. These fault systems could also be considered to bring the limestones of the Pindos zone into contact with the carbonate rocks of the Tripolis zone although, because of the greater thickness of the flysch in these areas, it is less likely.

These areas where there is a lower probability of hydraulic continuity between the two aquifer systems are also shown on the map of Figure 10.4.

The absence of large springs emerging in the eastern and north-eastern parts of the basin which would discharge the limestone masses outcropping there indicates that the groundwater of these Upper Cretaceous limestones, or at least of the greater part of them, must percolate downwards along various fault zones to the deeper aquifer system developed in the carbonate rocks of the Tripolis zone.

The Panagia and Opiste Panagia springs are situated closer to these areas but the possibility that they could be points of discharge of these limestone outcrops is excluded, as it has been proved that they discharge one of the karstic aquifers (aquifer No.1, see Fig 11.8) developed in the

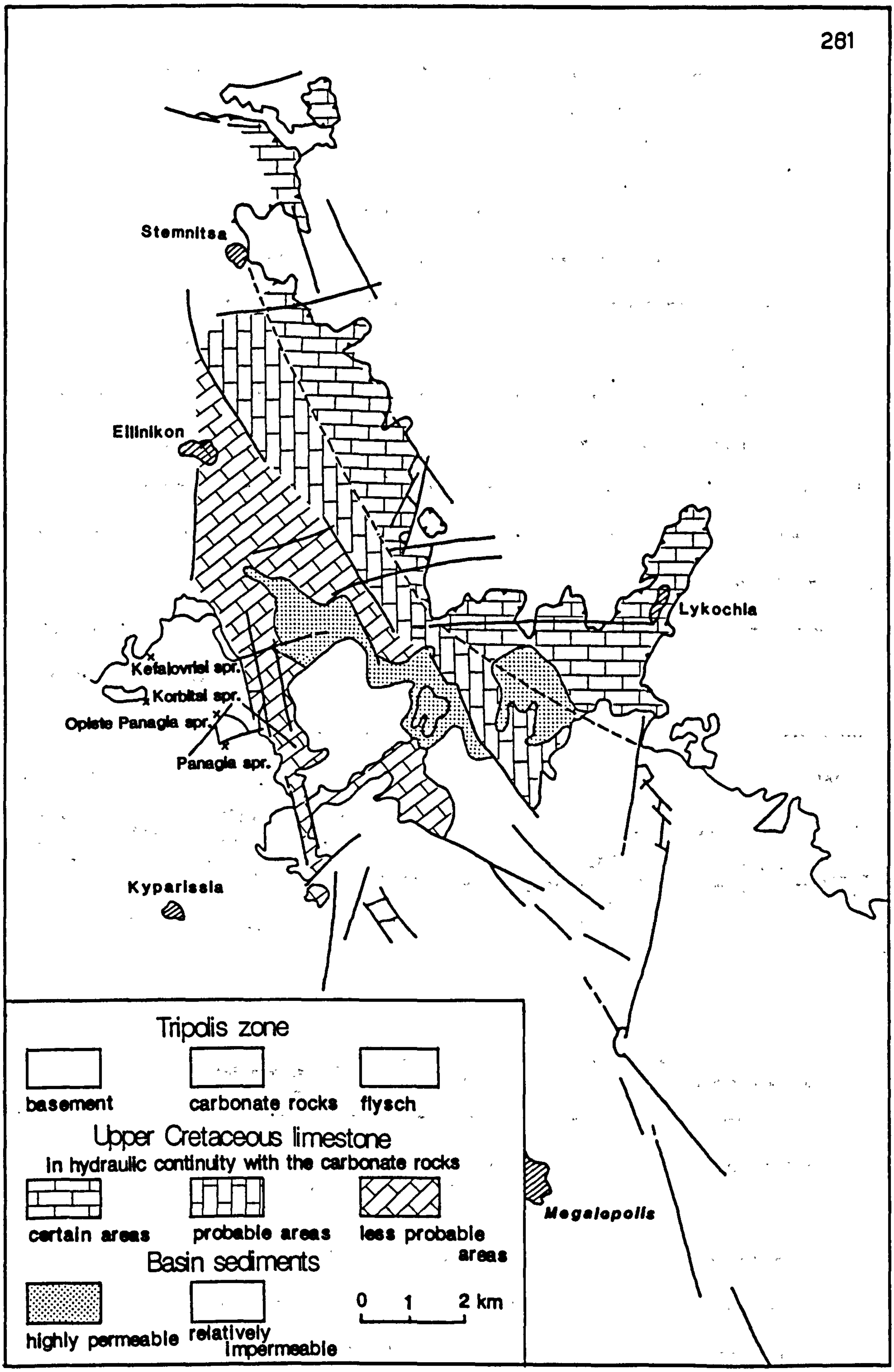


Fig 10.4 Map of the areas where the Upper Cretaceous limestone of the Pindos zone is in hydraulic continuity with the carbonate rocks of the Tripolis zone.

vicinity of the Kyparissia field (see also the subsequent section, 10.5.4).

10.5.3 The Kefalovrisi and Korbitsi springs

From the arguments developed in the previous sections, it can be clearly seen that an unequivocal answer to the major problem arising on this side of the basin, ie the determination of the extent of the aquifers and the direction of their discharge, is not possible.

The Kefalovrisi and Korbitsi group of springs, situated at the northern margin of the basin appears, based on the structure of the area, to be fed from the limestones of the structural-hydrogeological unit which extends in a N-S direction to the west of the village of Ellinikon. Further contribution of water to their discharge from other limestone masses is highly probable.

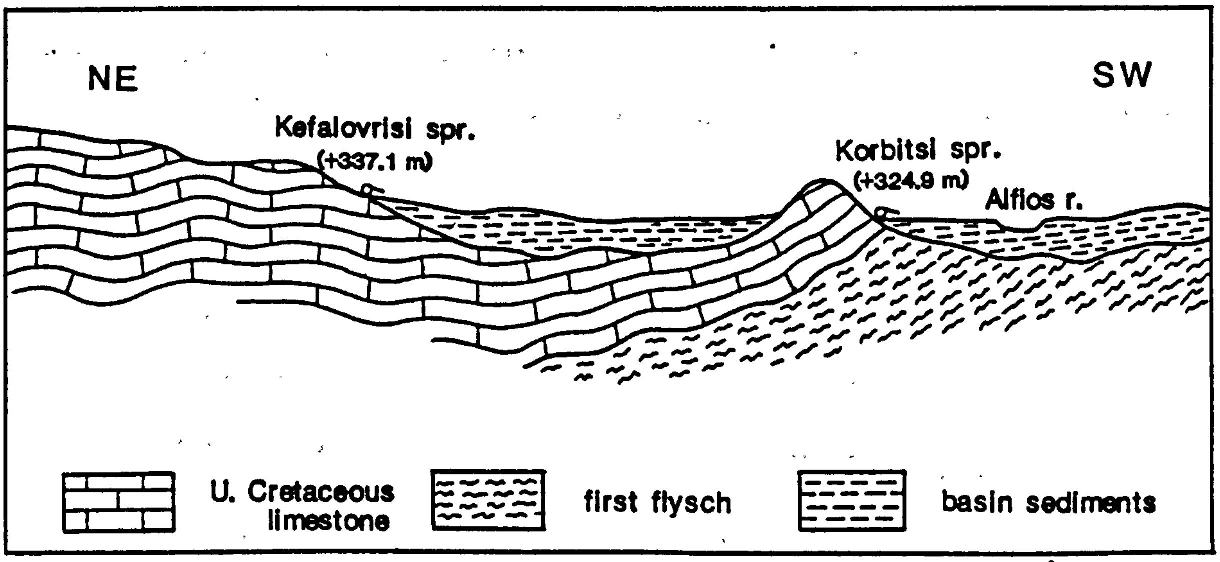


Fig 10.5 Schematic geological cross-section of the northern part of the Megalopolis basin (section a on Fig 10.1).

The Kefalovrisi and Korbitsi springs must be two different points of discharge of the same karstic body. The latter is almost a contact spring, flowing at an elevation of 324.9 m. It issues at the lowest altitude of any spring within the basin. The former is an overflow spring, flowing at an elevation of 337.1 m (Fig 10.5). Both springs emerge through fissures in the limestone.

The Kefalovrisi spring consists of two springs. The smaller is situated 100 m south of the larger spring and has a very low discharge. The larger is one of the largest springs issuing from the Upper Cretaceous limestones of the Pindos zone within the study area. It exhibits great variations in its discharge rate during the year, its maximum flow being about 20 times that during the dry season (graph a, Fig 10.6a).

The discharge of the Korbitsi spring is, on the other hand, relatively constant, its discharge rate during the wet season being just double that during the dry season (graph b, Fig 10.6b).

During the wet season, most of the water issues from the Kefalovrisi spring because it is located closer to the limestone masses which feed these springs. The great variations in the discharge rate of the Kefalovrisi spring indicate that these springs are of conduit feeder type.

An attempt was made to estimate the extent of the limestone outcrops which must feed these springs by using the equation commonly used for the calculation of the hydrological balance of a given spring, ie

$Vs = A \times P \times Ie$ or, modified, $A = \dfrac{Vs}{P \times ie}$ where,

Vs = the volume of the water discharged in a hydrological year (October-September) from a given spring,

A = the area of the limestone outcrops feeding this spring,

P = the precipitation in the respective year and

Ie = the coefficient of effective infiltration.

For the coefficient of effective infiltration, a value of 55%, as

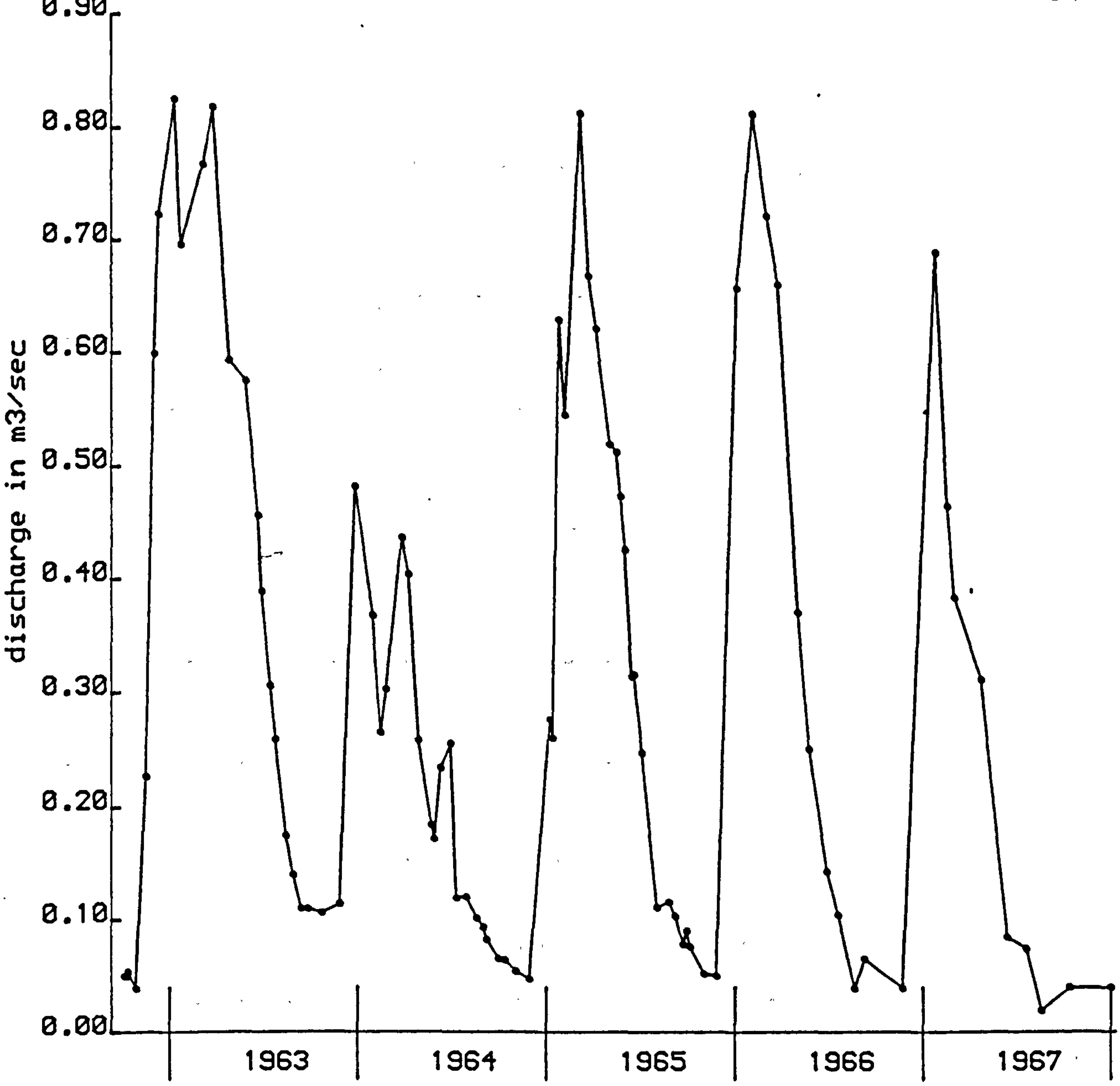


Fig 10.6a Hydrograph of the Kefalovrisi spring.

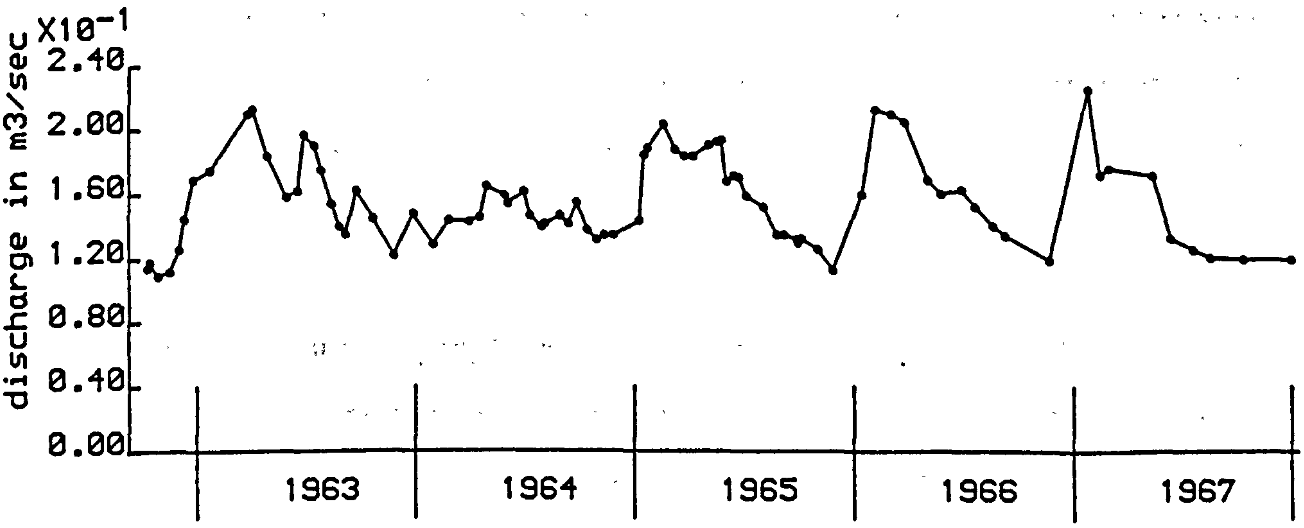


Fig 10.6b Hydrograph of the Korbitsi spring.

calculated for the Upper Cretaceous limestones (Section 8.3) was used. (The annual discharge of these springs was obtained by planimetering the area of their respective hydrographs.) The precipitation values used are given in Table 10.1.

Hydrological year	Volume of water discharged $\times 10^5 m^3/yr$	Coefficient of effective infiltration	Precipitation (at Karytena station) mm	Feeding area km^2
1962-63	168.0		1337	22.8
1963-64	90.4		903	18.2
1964-65	131.4	0.55	990	24.1
1965-66	122.4		1008	22.1
1966-67	86.4		997	15.8
Mean 1962-67	119.7	0.55	1047	20.6

Table 10.1 Calculation of the extent of the area discharging through the Kefalovrisi and Korbitsi springs.

The area feeding the Kefalovrisi and Korbitsi group of springs was roughly calculated at 20.6 km^2 based on the data of Table 10.1. The size of the area thus calculated differs greatly, however, from the approximation of 10 km^2 proposed for the feeding area earlier in this section, based on the structural-hydrogeological interpretation. It is therefore evident that, in addition to the structural unit extending west of Ellinikon known from the structural-hydrogeological interpretation to contribute water to the discharge of these springs, limestones outcropping further to the east must contribute water to their discharge.

10.5.4 <u>The Panagia (or Karvouniara) and Opiste Panagia springs</u>

These two springs, situated north of the Kyparissia field, flow on opposite sides of a limestone hill outcrop (Fig 10.7c) and are approximately 400 m apart. A small part of the water from these springs is used for irrigation, while the bulk of it flows directly into the Alfios river a few hundred metres to the west.

The Panagia spring is the larger and is at an altitude of 331.2 m. It is a contact spring and issues at the contact between the first flysch and the Upper Cretaceous limestone. Two smaller springs are found at an elevation of 328.0 m above sea-level, approximately 50 m west of the Panagia spring. Their discharge rate is significantly lower than that of the main spring.

The overflow type Opiste Panagia spring emerges at an altitude of 330.65 m at the contact between the recent basin sediments and the Upper Cretaceous limestones. The water emerges through fissures in the limestone at several points over a distance of 15 m along this contact.

Although these two springs are less than 400 m apart and appear to discharge the same karstic body, their discharge fluctuations, shown in Figure 10.6 (graphs a and b respectively), are dissimilar. Furthermore, although the Opiste Panagia spring is situated only slightly lower (0.55 m), its discharge is always almost half that of the Panagia spring.

It may be either that they are individual points of discharge fed from different karstic bodies with different hydraulic heads or that they are two successive points of discharge along the same flow channel and that the reduction in the hydraulic head, resulting from the discharge of the Panagia spring, affects the discharge of the Opiste Panagia spring situated further along the flow line. If the second explanation is adopted, then the groundwater movement must be roughly in a south to north direction.

This explanation is supported by the fact that both the increase and decrease in discharge take place earlier in the Panagia spring. Furthermore, according to the local people, the Panagia spring dries up

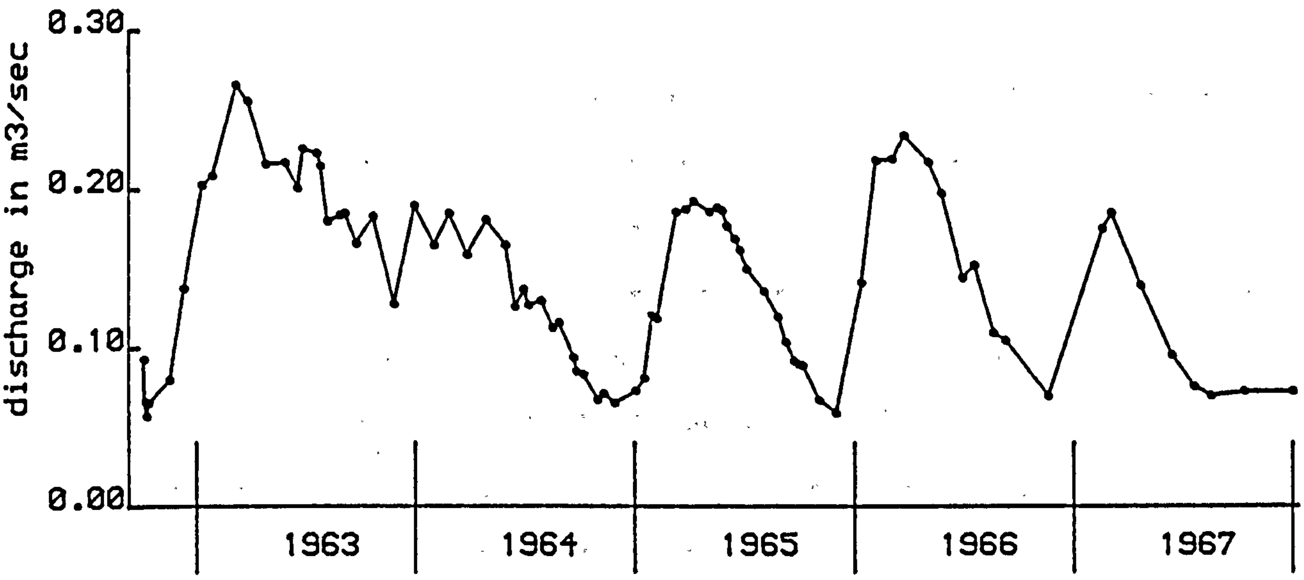


Fig 10.7a Hydrograph of the Panagia spring.

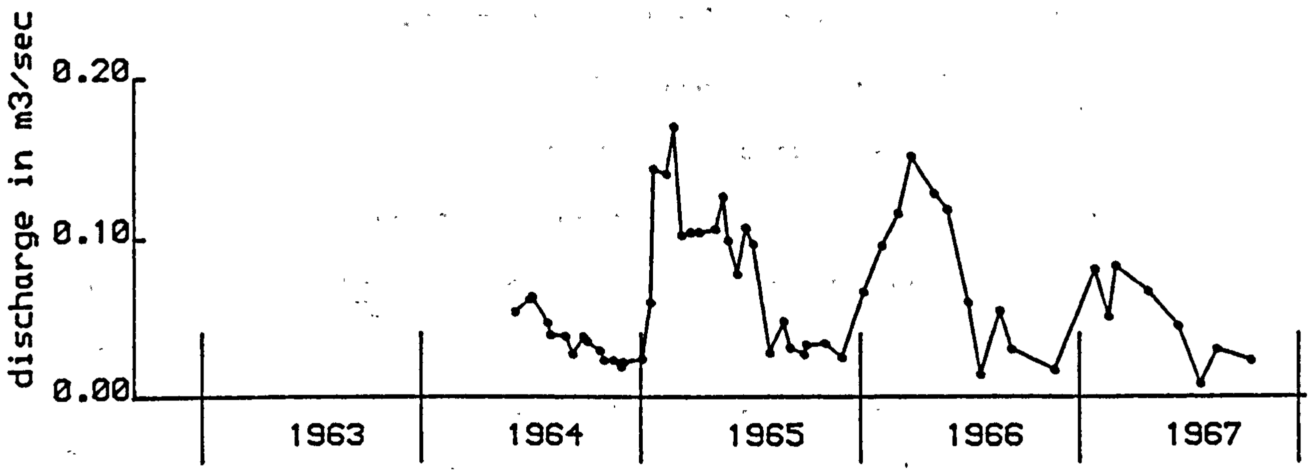


Fig 10.7b Hydrograph of the Opiste Panagia spring.

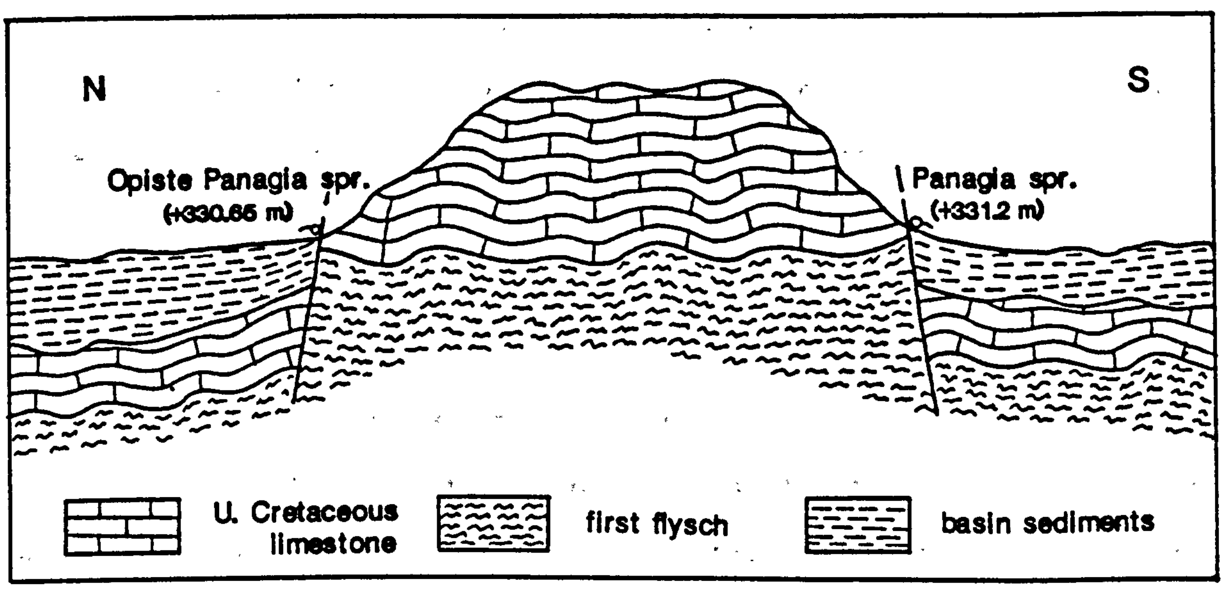


Fig 10.7c Schematic geological cross-section of the area around the Panagia and Opiste Panagia springs (section b on Fig 10.1).

much sooner than the Opiste Panagia spring. The two small flow springs, located to the west of the main Panagia spring, dry up last because they are situated much lower than the main springs.

The drying up of these springs was rare in the past. However, since 1975, when the Power Station began operation and the pumping wells started abstracting a relatively large amount of groundwater, 1400 m^3/h on average, from the karstic aquifers around the Kyparissia field to supply water to the station, these springs have dried up almost every year. This fact also indicates that this group of springs must be associated with the karstic aquifers of the Kyparissia field for when, due to intensive pumping, the hydraulic head in these aquifers falls lower than the elevation of these springs, they dry up. The hydrogeological and hydrochemical investigations (Section 12.1.4.1 and Chapter 14, respectively) established that these springs must be associated with an overflow from the aquifer developed at and to the east of the Kyparissia field.

The discharge of the Panagia and Opiste Panagia springs is relatively small for it to be considered that they discharge the whole of the limestone masses outcropping on the eastern and north-eastern sides of the basin. Furthermore, the amount of water percolating into the Upper Cretaceous limestones outcropping on these sides must be further increased since, in addition to the water infiltrating from rainfall, there is percolation downwards through sink holes, as around the village of Zoni and also to the north of the village of Palamari.

It should be reiterated here that the absence of large springs in the eastern and north-eastern parts of the basin indicates that the groundwater of the Upper Cretaceous limestones outcropping there percolates downwards to the deeper aquifer system developed in the carbonate rocks of the Tripolis zone.

The intermittent springs of Aghia Sotira, situated 100 m north-west of the bridge over the Alfios in the Kyparissia field, together with the spring situated by the western ramp of the same bridge and also a few other points of small groundwater flow along the Alfios river on the north-eastern side of the Kyparissia field, are associated with the aquifers developed in the vicinity of the Kyparissia field. Their hydrogeological regime will be discussed in the subsequent chapter.

10.6 Conclusions

In this chapter, the occurrence and the possibilities of groundwater moving laterally and contributing to the Kyparissia field have been investigated. The detailed presentation of the hydrogeological conditions and problems involved allows the following conclusions to be drawn:

1) The carbonate rocks of the Tripolis zone which outcrop on the northern, eastern and southern sides of the basin form an aquifer system deeper than that developed in the Upper Cretaceous limestones.
2) Part of the groundwater of the carbonate rocks of the Tripolis zone outcropping on the north-eastern side of the basin most probably discharges through those karstic springs situated at the bottom of the Lousios river valley, while it is likely that the groundwater of the carbonate rocks of the Xerilas river area discharge through the springs of Aghios Floros and Pidima some 15-20 km to the SSW.
3) The general direction of groundwater movement within the Upper Cretaceous limestones on the western and northern sides of the basin is roughly N-S and S-N (see Fig 9.1).
4) There is no contribution of groundwater to the Kyparissia field from the western, southern and eastern sides of the basin. On the

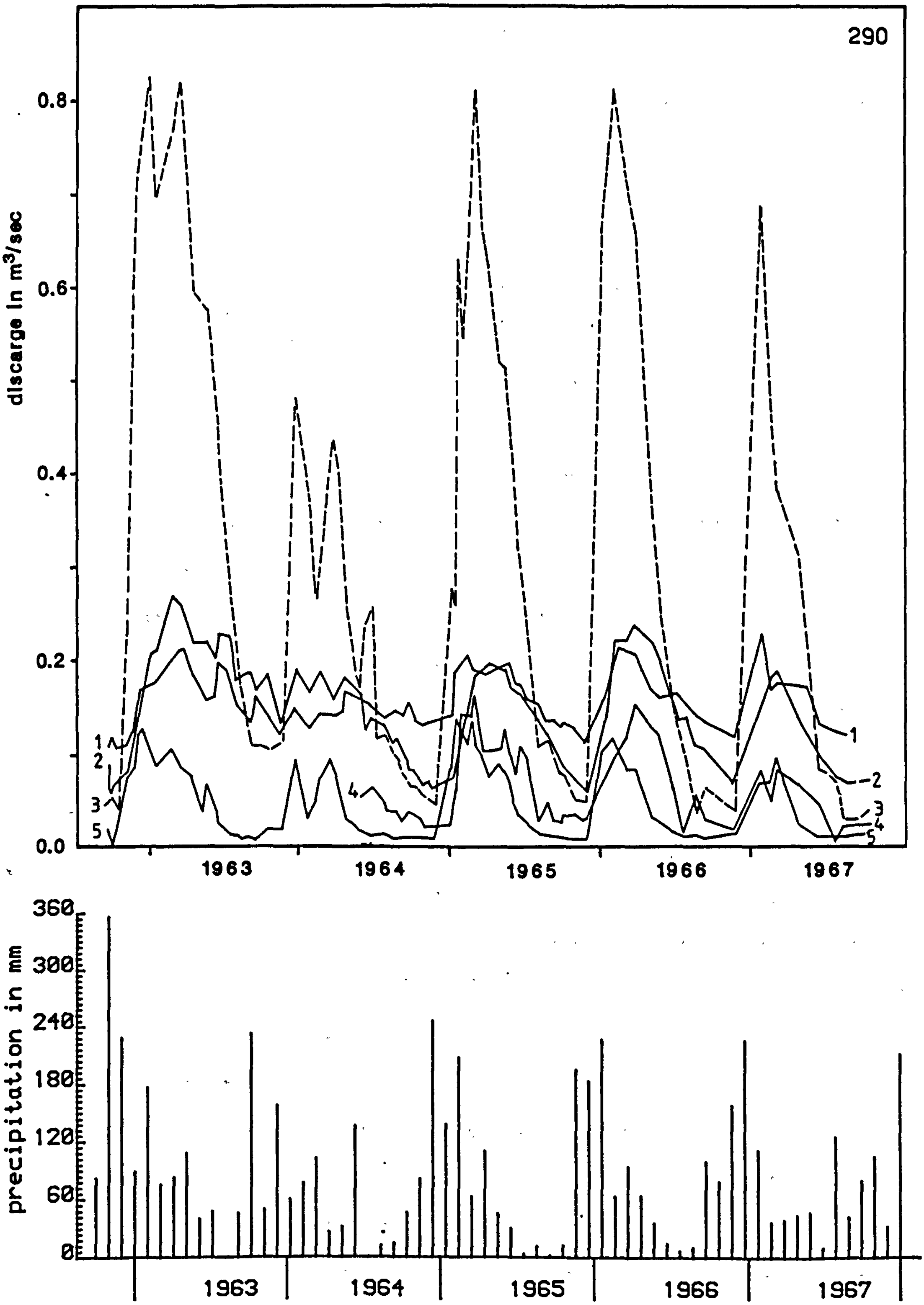


Fig 10.8 a) Hydrographs of the springs situated to the northern part of the basin of Megalopolis for the period 1962-67.
1. Korbitsi 2. Panagia 3. Zirali
4. Opiste Panagia 5. Palataki

b) Histogram of the monthly rainfall recorded at the Karytena Station over the same period.

western side, because of the thrust-slices structure, a number of karstic aquifers, usually elongated, stretching in a N-S direction and discharging through individual springs, have developed. On the southern side, where the carbonate rocks of the Tripolis zone outcrop, the groundwater percolates downwards to a deeper aquifer while, in the east, the separate outcrops of the Upper Cretaceous limestones, parts of the Pindic nappe, also discharge through individual springs.

5) The only probable areas from which groundwater could be contributed to the Kyparissia field are those lying on the northern and north-eastern sides of the basin where extensive Upper Cretaceous limestone outcrops occur. This possibility was examined and the following conclusions were drawn:

   a) Part of the Pindic nappe occurring to the north, west and south-west of the village of Stemnitsa is discharged through local springs.

   b) Over quite large areas, where the Upper Cretaceous limestones are in hydraulic continuity with the carbonate rocks of the Tripolis zone, the water percolates downwards to a deeper aquifer system. The extent of these areas is shown in the map of Figure 10.4.

   c) The remaining part of the limestone outcrop on these sides of the basin - most probably that part extending westwards from the village of Ellinikon - discharges through the karstic springs of Kefalovrisi and Korbitsi.

6) The lack of large springs in the eastern and north-eastern parts of the basin, which would discharge the Upper Cretaceous limestones outcropping on these sides of the basin, indicates that the

groundwater of these limestones percolates downwards to the deeper aquifer system, eg through fault systems.

7) The Panagia and Opiste Panagia springs, located north of the Kyparissia field, are closely inter-related and constitute overflow points of discharge of the karstic aquifers developed in the vicinity of the Kyparissia field.

CHAPTER 11: GROUNDWATER OCCURRENCE IN THE KYPARISSIA FIELD

11.1 Introduction

The geological and structural framework of the Kyparissia field was given in detail in Chapter 5. The main features are here briefly reviewed.

The subsurface bedrock topography, as determined by the boreholes sunk in this area, is of relatively high relief. The Sikalia ridge, which forms part of a range of buried hills extending in a general SW-NE direction, together with the Lapatou and Lagada sub-basins, are the main topographical features of the bedrock of the Kyparissia field (Fig 5.4).

The nature and the structure of the bedrock of the Kyparissia field was interpreted partly from the reports of the boreholes extending down into the bedrock and partly from the results of the geophysical investigation carried out in 1985. The bedrock is made up of formations of the Pindos zone, partly of first flysch and mostly of Upper Cretaceous limestones. The western and northern parts of the bedrock are built up from a series of elongated, irregularly repeated first flysch and Upper Cretaceous limestone bands, which are parts of the imbricate thrust-slice structure occurring here. The eastern and north-eastern parts of the bedrock, on the other hand, are built up of strongly folded Upper Cretaceous limestones extending over a long distance to the eastern side of the Kyparissia field as extensive outcrops, partially covered by the basin sediments.

The basin fill of the Kyparissia field consists mainly of sediments of the Apiditsa stage and the lignite-bearing Marathousa beds and partly of the Megalopolis beds. The lignite occurs here in the form of a thick horizon in which the interbedded clay, silt and marly layers are not of significant thickness. In places, it comes into contact with or lies directly on top of the limestones (Fig 5.2). A large part of the Kyparissia field is covered by the terrace gravel-bodies of the Alfios river.

Three types of aquifer are developed in the vicinity of the Kyparissia field, as follows:

1) A shallow aquifer is developed in the terrace gravel-bodies. It is in close hydraulic relationship with the surface water (ie the Alfios river and minor tributaries in the area) and also with the karstic aquifers developed at a lower level.

2) Local aquifers, generally of minor extent and small thickness, often disconnected, with different hydraulic heads, are developed within the permeable parts of the basin sediments of the Apiditsa and Marathousa beds.

3) Finally and most importantly, karstic aquifers are developed in the Upper Cretaceous limestones of the bedrock beneath the basin sediments.

The occurrence of these different aquifers and the hydraulic properties of the karstic aquifers will be discussed in subsequent sections.

The major hydrogeological problem associated with the mining of the lignite of the Kyparissia field has been evident since early investigations of the possible exploitation of the lignite deposits (Gold Report, 1963), namely that the karstic aquifer developed in the area has a pressure head at a much higher elevation of 330-340 m than that of the operational floor of the lignite workings at 280 m. It is, therefore, necessary to lower the water table level of the karstic body by 60 to 70 metres to allow the mining of the lignite in this area.

11.2 Aquifers in the terrace gravel-bodies

The Alfios river flows on the eastern side of the Kyparissia field crossing it over short distances in two places.

The Alfios, together with its tributaries (eg the Elisson stream), is associated with a band of varying width, made up of the recent gravel body and the old river terraces, ie the Potamia (Upper), the Thoknia (Middle) and the Lower terrace. These terrace gravel-bodies are of great extent to the north-east and to the south-east of the Kyparissia field, as around the village of Thoknia, where their total width is approximately 4 km and also in the Kyparissia field itself, most of which they cover. The Potamia terrace only forms a small part of the whole make up of terrace gravel-bodies. It outcrops along the eastern bank of the Alfios river, south-east of the Kyparissia field, and also on both sides of the Elisson stream.

All these bodies consist, in general, of gravels, sands, clays and silts, although there are considerable differences between them in lithology (ie in the size, origin and degree of roundness of the pebbles) and in the proportion of finer clastic material (clay, silt) present. A higher proportion of clay exists in the Thoknia and especially in the Potamia terraces where it is partly derived from the decomposition of the sandstone pebbles. The upper part (old flood-plain of the river) of the Thoknia and Lower terrace, of a relatively small thickness, consists of sands, clays and silts. The presence of this horizon greatly reduces the infiltration capacity of these terraces.

Generally, all these bodies are of good permeability and form aquifers of medium (Potamia terrace) to high (Lower terrace) productivity (see also Chapter 9). Given the lateral and vertical variations in their lithology, areas of higher permeability in the form of channels or lenses must exist within them.

All these terrace gravel-bodies can be considered as a single hydrogeological unit, since a hydraulic connection between them has been recognised. The aquifer formed within these bodies is in close hydraulic continuity with the surface water of the Alfios river and its minor tributaries. During the wet season, when the discharge of the Alfios river is higher, corresponding to a great elevation in the level of water running within its course, a transmission of water towards the terrace bodies takes place (influent conditions) while, during the dry season, when the Alfios river discharge declines, water from these bodies discharges into the river, contributing to its base-flow (effluent conditions). As the water table in the aquifer of the terrace gravel-bodies falls, a decrease in the amount of water draining into the river occurs.

Over most of the area, these bodies overlie the relatively impermeable sediments of the Marathousa beds. However, for short distances, as to the north of the Kyparissia field before the Aghios Georgios gorge and mainly to its eastern side around and north of the bridge over the Alfios river at Kyparissia, they lie directly on the Upper Cretaceous limestones which outcrop in these areas (Fig 12.2). Here the Alfios river runs over these limestone outcrops. A close hydraulic relationship between the aquifer formed in the terrace gravel-bodies, the Alfios river and the karstic aquifer evidently exists here.

Further discussion of the occurrence and the properties of the aquifer developed in the terrace gravel-bodies will be given in Chapter 12 when the karstic aquifers with which they are hydrogeologically associated are examined.

11.3 Aquifers in the basin sediments (Apiditsa and Choremi stages)

A detailed hydrogeological investigation was not undertaken into the hydrogeological conditions and properties of the aquifers developed in the unconsolidated basin sediments of the Apiditsa and Choremi stages, due to the belief that the amount of water borne in these lowly permeable to aquiclude formations does not constitute a major hydrogeological problem for the future open mine. The author agrees with Georgen (1978) who stated, based on experience gained at the open pit of Thoknia to the south-east of the Kyparissia field, that only layers of minor thickness and medium permeability occur in the unconsolidated basin fill of the Kyparissia field.

Here, only a brief report is given on the hydrogeological conditions and the permeability of the formations of the Apiditsa stage and the Marathousa and Megalopolis beds of the Choremi stage occurring in the Kyparissia field. It is based on their lithological composition and nature and on field observations and data reported in previous studies or obtained during the present study.

A basal slightly cemented gravel formation occurs almost everywhere, overlying the bedrock of the Kyparissia field. Where it rests on the Upper Cretaceous limestone bedrock, this formation consists largely of limestone gravels, is highly permeable and is considered to be in hydraulic continuity with the karstic aquifers developed in the limestone it overlies. When it overlies the first flysch bedrock or the areas adjacent to it, it is rather clayey and consists of sandstone, possible calcareous boulders and pebbles and also of sands and clays derived from the decomposition of the sandstone of the first flysch. In these areas, it is a relatively impermeable formation.

The Apiditsa stage, consisting of alternations and lateral transitions of clays, sands and loosely cemented pebbly beds, in which the pebbles are almost exclusively psammitic, is overall an aquiclude formation. In places where banks consisting mainly of sands and pebbles with a low clay content are present, a certain degree of permeability must occur. It was noted in the Gold Report (1963) that mud losses or artesian flow were only reported for a few of the boreholes during the investigative work and occurred in those places where lenticular beds, of limited extent, of gravels and/or medium to coarse-grained sands were encountered. The Apiditsa stage as a whole should, therefore, be considered impermeable.

The Marathousa beds are also regarded on the whole as an impermeable formation, as they consist of lacustrine marls, clays, humus clays and a thick (50-70 m) seam of lignite with interbedded, unproductive layers of a relatively small thickness. However, a certain degree of better permeability can be assigned to the interfingering layers or lenses of coarser clastic material occasionally occurring in the lower parts of the Marathousa beds. The lignite beds themselves are also permeable in those places where they are fragmented and cracked, eg by wide fissures which often appear in the lignite beds when they dry up.

The Gold Report (1963) stated that some parts of the lignite and, locally, some of the lime silt beds (silt with a high content of mollusc shells), must be considered as permeable, for total or partial losses of mud flush were often reported during the investigative work at the Sikalia ridge and in the Lapatou sub-basin. Furthermore, in a few of the boreholes, there was a low artesian flow for a few days from the Marathousa beds. Mud losses were not, however, reported for the Lagada sub-basin, inside the sediments of the lignite series, except in a few boreholes at its margin. The report stated that, in spite of the low permeability present in places in the lignite beds, the lignite series as a whole can be considered impermeable over wide aeas.

As the lignite lies directly over the limestone at the Sikalia ridge, with no impermeable stratum present in between (Fig 5.2), the aquifer developed in the partly permeable lignite must be in continuity with the karstic aquifer.

The Megalopolis beds overlie the Marathousa beds. In most places, only patches of the Megalopolis beds are to be found as, being the youngest and therefore the highest formation, it was the most susceptible to erosion. The Megalopolis beds consist of gravels, sands, clays and silts and are, in general, a low permeability formation.

A spring with a very low discharge rate was found, originating from the Megalopolis beds at their point of contact with the Marathousa beds, approximately 500 m to the south of the village of Kyparissia. In places the Megalopolis beds are in hydraulic continuity with the adjacent terrace gravel-bodies, resulting in a transmission of water from the former to the latter.

The information given in the previous paragraphs shows that a small number of aquifers of relatively small extent and thickness must have developed in the permeable parts of the loose sediments filling the Kyparissia field.

A small number of boreholes, those numbered 60/60, 62/60, 63/60, 66/60, 74/60, 75/60 and 319/62, were sunk in the Kyparissia field and cased by filters in order to be used as observation wells for monitoring the groundwater level of the aquifers developed in the loose basin sediments, ie the Marathousa beds.

Unfortunately, data from the measurements taken of the water table from these boreholes are not available, except for the borehole 319/62. The Gold Report (1963) referred to the groundwater levels recorded in these observation wells during the period 1960-63, stating that the conclusion can be drawn that no groundwater with uniform pressure conditions exists in the permeable parts of the lignite series, as completely different levels, from 332 m up to 361 m above sea-level, were measured simultaneously. It may be assumed that several permeable horizons exist in the lignite. These horizons are mostly situated near the margins of the field and are not connected to each other.

The hydrograph (see Section 11.4.3.3 for details) of the observation well 319/62 (see Fig 11.4 for its position) for the period 1975-81 is given in Figure 11.1. The groundwater level shows only small fluctuations during this observation period lying on average at an elevation of 338 m.

The observation wells 372 and 376 (Fig 11.4) were drilled to serve as observation wells for the karstic aquifers developed under the Kyparissia field. Their well-hydrographs (Figs 11.2 and 11.3) present a completely different type of fluctuation from the pattern seen in the karstic aquifers into which these wells were sunk and which was recorded using observation wells adjacent to them. Thus, it must be assumed that these wells became plugged at a certain depth above the limestone surface and that the groundwater levels recorded correspond to shallow aquifers occurring in the unconsolidated sediments filling the Kyparissia field. It is, however, difficult to ascertain how this might have occurred as, according to the contractors' report, the blind part of the casing extended down to the limestone surface.

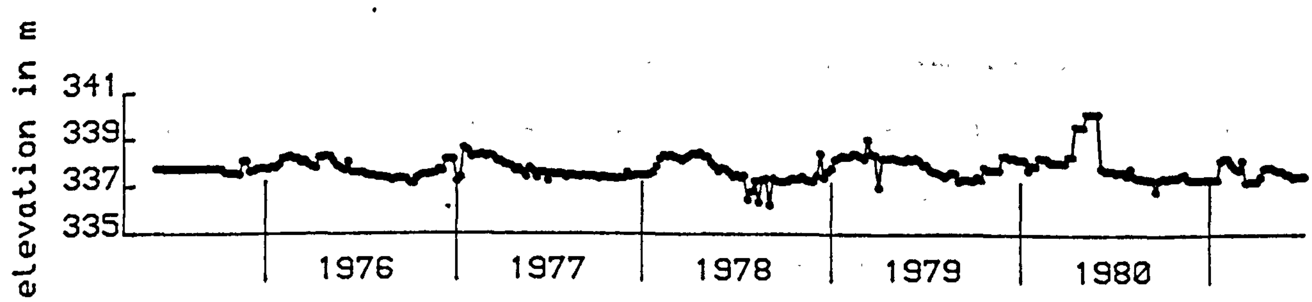


Fig 11.1 Groundwater hydrograph of well 319/62.

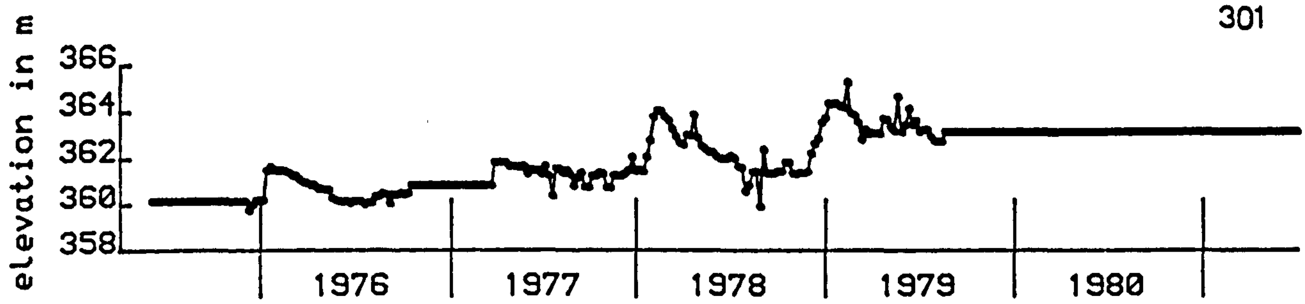


Fig 11.2 Groundwater hydrograph of well 372.

Characteristic is the case of well 376. The study of its well-hydrograph (Fig 11.3) shows that the well may have been unplugged, either artificially or naturally, for a short time, for the fluctuations and the groundwater level recorded in it followed the fluctuations of the groundwater of the karstic aquifer No. 3 into which it was sunk (see Fig 11.8 for the extent and notation of the aquifers).

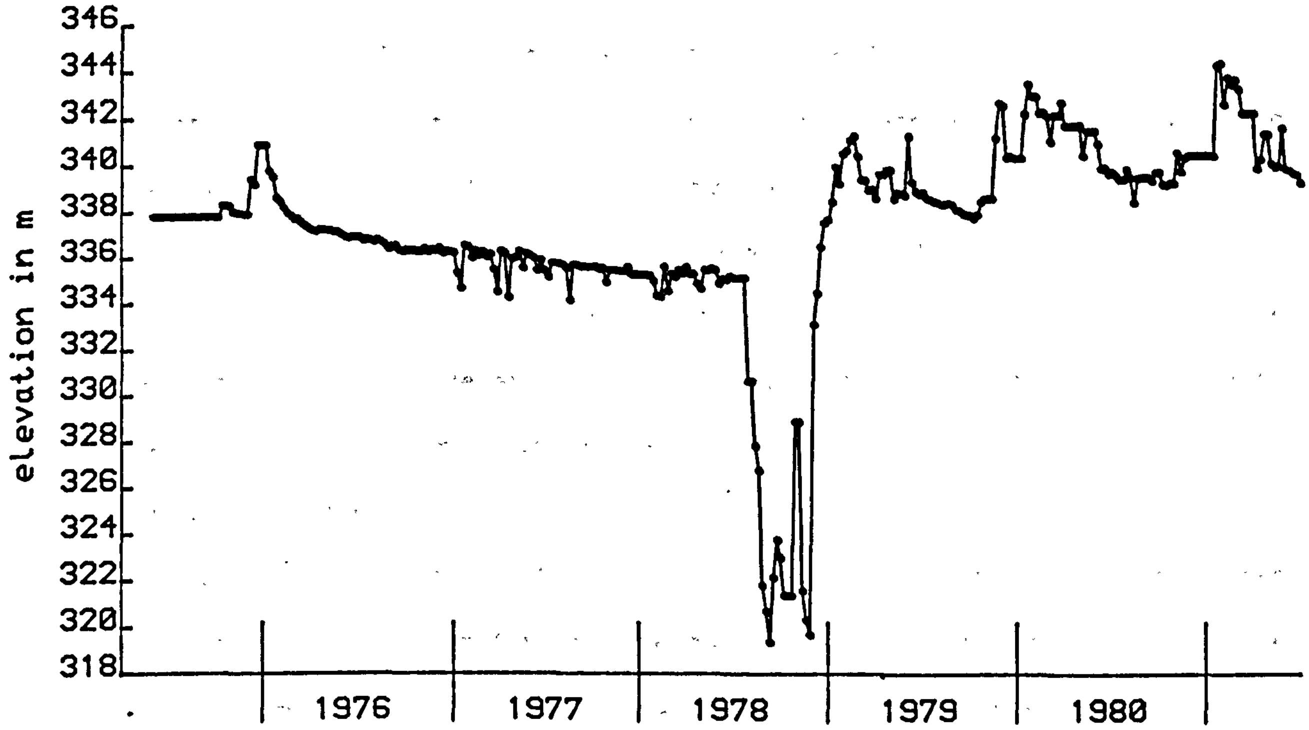


Fig 11.3 Groundwater hydrograph of well 376.

The different groundwater levels recorded in these three wells (mean height at well 319 338 m above sea-level), at well 372 362 m above sea-level and at well 376 336-340 m above sea-level) must represent three different aquifers developed in the loose sediments filling the Kyparissia field.

11.4 Karstic aquifers

11.4.1 Introduction

11.4.1.1 Results of the previous investigations

A relatively thorough hydrogeological investigation was carried out by the firm of O. Gold (1963), as part of the exploratory work for the exploitation of the lignite. The results were reported in Volumes 8 and 9, hydrology and annexes respectively, and also in Volume 10 of the additional hydrological investigations.

From the early stages of the investigation it was realised that, in addition to the usual hydrogeological problems associated with mining from an open pit, major problems also arise from the presence of a karstic body developed in the Kyparissia field with a piezometric surface or a water table lying at an elevation of 330-340 m. Since, over most of the area, there is no dense horizon of impermeable strata between the limestone bedrock/aquifer and the lignite - the operational floor in a few places lies between 270 and 280 m above sea level - it was pointed out that, in order to guarantee safe mining in the district of the so-called Sikalia ridge and the area around it, it would be necessary to lower the karstic groundwater level by a total of 60-70 m below the present groundwater level.

From the evaluation of the data on the karstic springs in the area (situation, flow, water temperature and quality), from the records of the drilling operations and also from the results of the pumping tests obtained, it was concluded that the limestone is saturated with groundwater to the surface level of the basin of the Kyparissia field. The karstic water underneath the basin filling must be considered as being under pressure, while the karstic water body must be considered to be large and possibly far-reaching with relatively uniform pressure conditions prevailing.

It was concluded, based on the geological map (1:25,000) prepared by Lüttig and Vinken in 1960 (included in the Gold Report, 1963), that the karstic body developed in the Kyparissia field was delimited as follows:

1) in the south, by a deeply eroded gully filled with basin sediments.
2) in the west, by an extended flysch zone - referred to as first flysch in the present study - stretching from SSW to NNE and outcropping on this side of the basin. On the western side of the Kyparissia field, it was pointed out that the huge body of calcareous rocks is intersected by narrow bands of first flysch and that it is likely that a formation of separate karstic bodies with their own peculiar groundwater characteristics occurs here.
3) in the north, by the water divide bordering the Lousios river which limits the extent of the karstic water body.
4) in the east, the limit of the more or less uniform karstic aquifer was not clearly defined. Thus, an additional geological map (to a scale of 1:25,000) of the area from north of the village of Karytena up to the village of Stemnitsa and reaching eastwards as far as the villages of Lykochia and Vangos was produced in spring 1963. Based on this, it was claimed that the 'light-coloured' limestones (ie Upper Cretaceous limestones in the present study) are delimited to the east, between the villages of Stemnitsa and Vangos, by a narrow zone of flysch-like rocks - the 'tectonic block' formation, according to the present study - which practically seals off the karstic water body which reaches down to the Kyparissia field. It was therefore concluded that the limestone formation - referred to as the carbonate rocks of the Tripolis zone in the present study - adjoining this 'flysch zone' on the eastern side forms another hydrogeological unit.

Based on the geological mapping and the interpreted limits of the karstic body forming a hydrogeological unit, it was calculated that a limestone surface of an area of about 70 km^2 is exposed to infiltration following precipitation, estimated at 1000 mm/year for this area. Based on a coefficient of effective infiltration of 50%, the quantity of water infiltrating was calculated to be in the region of 30 x 10^6 m^3/year.

As regards the influxes from the surface water of the Alfios river, it was decided that in those areas where the river runs over the limestone outcrops, even for short distances, it would be necessary to seal off the river bed artifically in those parts where the river itself does not seal off its channels down to the aquifer, in order to prevent the river water from percolating down into the karstic groundwater once the water table of the karstic aquifer had been lowered, thus causing the hydraulic gradient always to be from the Alfios river to the karstic aquifer.

The areas where the Alfios river water would be likely to percolate downwards are those situated around the Kyparissia bridge, near the Aghios Georgios gorge, near the Panagia spring and, less probably, south-east of Karytena.

The karstic water which must be removed in order for the lignite adjacent to the limestone to be mined includes permanent water (ie that which fills the pores and hollows of the karstic limestone (their porosity estimated at 5%) up to the present water table level) and also the water regenerating from infiltrating precipitation which, as shown above, was calculated to be between 30 and 35 x 10^6 m^3/year and which is at present discharged through the karstic springs situated around and to the north of the Kyparissia field. After considering the method of dewatering (pumping, construction of a gallery) to be employed and making a few assumptions regarding the new shape that the karstic water table would adopt as a result of these new conditions, the quantity of permanent water which would have to be removed was estimated to be between 85 and 210 x 10^6 m^3.

Lüttig and Thiele (1968), in their report on potential sources of water supply to the power station (units I and II) and referring to the hydrological conditions of the karstic aquifer developed in the Kyparissia field, reported results the same as those contained in the Gold Report (1963) in which the investigations (carried out during 1962 and 1963) at the karstic springs, in the boreholes and via pumping tests, showed that

1) the limestone contains groundwater up to the level of the top surface of the Kyparissia basin,
2) the karstic groundwater storage can be considered large and the karstic body of great extent with more or less uniform pressure conditions, and
3) the northern part of the basin represents the recharge area of the aquifer.

The amount of water entering the aquifer from infiltration following precipitation over the catchment area (70 km^2) of the karstic rocks is equal to 30 to 35 x 10^6 m^3/year and is balanced by the total discharge of the karstic springs situated in the Megalopolis basin, to the north of the village of Kyparissia.

Based on these considerations, Lüttig and Thiele (1968) proposed that the amount of water required to supply the power station could easily be derived from the karstic body through a few (probably five) pumping wells, situated between the Sikalia ridge and the eastern side of the Alfios river, where better conditions for the abstraction of water are present.

A detailed and comprehensive investigation of the groundwater surface water budget of the Megalopolis basin and the Alfios catchment in general was carried out by Karkulias (1975). His main conclusions are as follows:

Two types of aquifers are developed within the Megalopolis basin occurring in

a) the unconsolidated basin fill, and

b) the karstified limestone beneath and at the margins of the basin.

A hydraulic continuity exists in part between these two types of groundwater. The groundwater in the most impermeable unconsolidated sediments is primarily confined, except in those sediments associated with the river system. The permeability of the unconsolidated sediments varies greatly depending on the composition.

The deep karstification of the permeable to highly permeable limestone allows the development of large bodies of karstic groundwater. The water in these bodies is under pressure beneath the basin fill. The head elevation is represented primarily by the 330 m altitude of the karstic springs to the north of Kyparissia.

The rate of replacement of the aquifer for a hydrological year accounts for about 285 mm of the 1170 mm mean annual precipitation (mean value over 11 years). The mean actual evapotranspiration is calculated to be approximately 54% (or 635 mm) of the precipitation.

Determinations of tritium content show a very long in situ residence time (40 to 140 years) for the karstic groundwater. A chemical investigation indicated that, in part, the surface and groundwater show distinct differences.

Georgen (1978) also considered that the karstic body developed beneath the Kyparissia field had a catchment extending far beyond the field to the east and north.

After he had drawn the groundwater hydrographs of 18 wells situated in the central, eastern and southern parts of the Kyparissia field and penetrating the limestone bedrock, for the years 1963-66 and 1974-76 and also the maps of the lower and the higher groundwater levels for the years 1963-64 and 1976, he concluded that the minor reduction in pressure of the karstic pressure head of approximately 6.0 m, from 340 m above sea-level in June 1963 to 334 m in February/March 1976, was due exclusively to the permanent drawdown caused by the operation over five years of the power plant wells.

All the findings and calculations given by the Gold Report (1963) concerning the amount of water to be removed were widely accepted by Georgen (1978) (ie volume of groundwater in the aquifer (storage water) = 3.5×10^6 m^3 per metre of lowered water table plus an additional volume of 35×10^6 m^3 of annual replenishment of groundwater originating from infiltrating percipitation).

Based on these assumptions and calculations, Georgen proposed a detailed time-schedule concerning the construction and start of operation of a step by step dewatering of the karstic body through the 25 years of the mining period. According to this, the lowering of the water table of 60 to 70 m could be achieved by a total of 22 wells arranged in 3 or 4 batteries:

- a western battery of 6 to 8 wells, equipped with pumps of a capacity of 100 m^3/h.
- an eastern battery of 6 to 8 wells, equipped with pumps of a capacity of 900 m^3/h, the higher capacity being required due to the fact that the maximum inflow of groundwater is to be expected from this side of the field.

- a central battery located along the Sikalia ridge of 3 wells, equipped with pumps of a capacity of 100 m^3/h and, if required,
- an additional southern battery of 3 wells, equipped with pumps of a capacity of 300 m^3/h.

Finally, Spiliotis (1978), in a brief report, reviewed the results of the investigations carried out up to then, listed the various hydrogeological problems and proposed solutions concerning the mining of lignite by means of an open pit in the Kyparissia field.

11.4.1.2 Present interpretation

A completely different interpretation of the hydrological extent and occurrence of the karstic aquifers developed in the Kyparissia field is proposed in the present study.

The bedrock of the Kyparissia field consists of formations of the Pindos zone. The central and western parts of the bedrock of the Kyparissia field are built up of imbricate thrust-slices, this structure being present along the whole western side of the Megalopolis basin. The presence of this type of structure beneath parts of the Kyparissia field suggests the occurrence of a number of separate limestone subcrops in these parts and this, under certain conditions, would in turn lead to the formation of individual hydrogeologically isolated aquifers.

From a hydrogeological point of view, the problem arising here, therefore, is to establish to what extent the proposed structure and distribution of the first flysch-limestone subcrops, as given on the map of Figure 5.7, correspond to the actual situation and, further, to what extent the separate limestone subcrops are in fact hydrogeologically isolated (ie form individual aquifers).

The solution to this major hydrogeological problem was found from the study of the form of the piezometric surface or, in places, of the water table of the karstic aquifers developed in the Kyparissia field and the pattern of the fluctuations of the groundwater levels in these aquifers (see Section 11.4.3) which were recorded by means of a great number (62) of observation wells (piezometers) sunk for this purpose throughout the Kyparissia field and also by a detailed hydrochemical investigation (see Chapter 14).

11.4.2 Geological and geophysical determination of the extent of the karstic aquifers

It has already been pointed out that the type of structure shown by the Pindos zone within the study area is of fundamental importance for the determination of the hydrogeology of the various parts of the area, as it controls the movement of the groundwater within the Upper Cretaceous limestones.

As has already been described in detail in Section 4.4.2, the Pindos zone exhibits a different structure and development on opposite sides of the Megalopolis basin, resulting in different hydrogeological regimes. Thus, on the western side of the basin, the Pindos zone presents a structure of imbricate thrust-slices of first flysch and Upper Cretaceous limestones, irregular both in thickness and extent. The limestone outcrops mostly form individual aquifers with the groundwater moving roughly in a N-S direction and discharging through a great number of springs. On the eastern side of the basin, however, the Pindic nappe consists almost exclusively of strongly folded Upper Cretaceous limestones. Where the Upper Cretaceous limestones are overthrust onto the carbonate rocks of the Tripolis zone, the groundwater percolates downwards to a deeper aquifer system while, in places where these limestones are overthrust onto the flysch of the Tripolis zone, it discharges through contact springs.

The geological mapping of the narrow area around the Kyparissia field revealed that the type of structure and development of the Pindic nappe present over the whole western side of the Megalopolis basin also occurs on the western and northern sides of the Kyparissia field. The presence of thrust-slices in the north of the Kyparissia field, together with the fact that the thrust traces follow a roughly N-S direction, led to the conclusion that this type of structure must extend southwards, beneath the Kyparissia field. In the eastern and north-eastern parts of the Kyparissia field, on the other hand, the bedrock is made up exclusively of Upper Cretaceous limestones, as concluded from the type of structure the Pindic nappe presents on the eastern side of the Kyparissia field (ie the same as that occurring on the whole eastern side of the Megalopolis basin).

The presence of the first flysch bedrock beneath the Kyparissia field was detected by a few boreholes (see Fig 5.3) deep enough to reach the bedrock and sunk during the investigative stage (1960-1963) in the central-western part of the field. According to the type of structure deduced to be present in these parts of the bedrock, these points of the first flysch must represent parts of elongated subcrops, extending roughly in a N-S direction.

A geophysical/geoelectrical investigation was proposed and was carried out for further investigation into the structure and the nature of the bedrock (ie distribution of the limestone and first flysch subcrops). The geophysical investigation confirmed the thrust-slice type of structure to be present in at least part of the bedrock of the Kyparissia field.

The most probable structure of the bedrock, together with the probable distribution of the first flysch and the limestone subcrops, is shown on the map in Figure 5.7.

11.4.3 Hydrogeological extent of the karstic aquifers

11.4.3.1 Introduction

The existence of a small number of karstic aquifers developed in the Kyparissia field was assumed as a basic premise in the first stages of the geological and geophysical investigations and was later confirmed.

The findings concerning the extent of these karstic aquifers were based on the study of the form of piezometric surface or, in places, of the water table within the Kyparissia field and also on the study of the type of fluctuations presented by the groundwater level in each of the observation wells.

More than sixty boreholes/observation wells (Fig 11.4), spread across the future mine area of the Kyparissia field and also to the north and east, were used to obtain information about the groundwater levels. Observation wells were chosen from those boreholes which penetrated the unconsolidated basin sediments and intercepted the limestone bedrock. They were cased in such a way (blind pipe down to the limestone surface) that the measurements taken referred only to the groundwater levels of the karstic aquifers. The existing production wells sunk in the area (F1 to F9) and also the wells F8/72 and F10/72 were also used as observation wells.

A few other wells, sunk mainly in the south-eastern part of the field, were cased in such a way as to give information on the piezometric surface or the water table of the aquifers developed in the loose basin sediments, the Marathousa beds. Unfortunately, these data are unavailable.

In a few of the wells, the recording of the groundwater level was started more than 25 years ago (in 1960), but valid and continuous data are only available for the period 1975-1983. The measurements of the

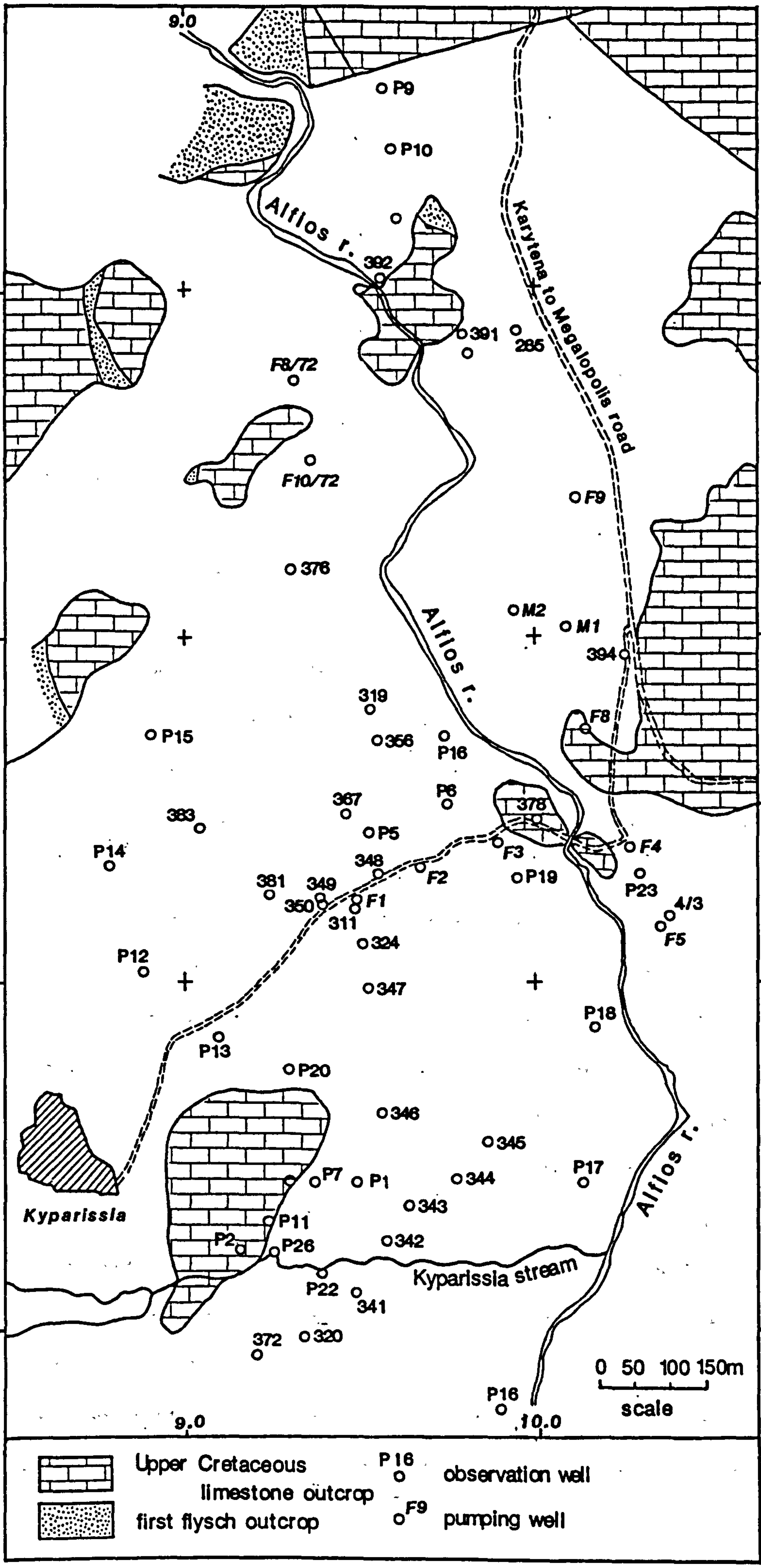


Fig 11.4 Location of the observation and production wells sunk in the karstic aquifers developed in the Kyparissia area.

groundwater level, which were provided by the Electricity Board, were taken on a weekly basis (every Sunday morning) up to 1981 and every two weeks for the period 1981-83. The depth of the groundwater level was measured using electric tape dippers.

The data provided for the period 1975-1981 have been analysed and studied as part of the present investigation. The methods of analysis used and the general conclusions drawn are presented in the subsequent Sections 11.4.3.2 and 3.

11.4.3.2 Form of the piezometric surface/water table

Contour-maps of the higher and the lower groundwater levels (ie at the end of the wet and the dry seasons, respectively) of the Kyparissia field and the area surrounding it were drawn for the period 1977-81 (an example of the maps drawn in given in Figure 11.5). The well hydrographs (see next Section) were used to obtain the dates when the piezometric surface/water table reached its highest or lowest levels. For the construction of these maps, the groundwater levels recorded at each well on those certain dates, as determined from the well hydrographs, were noted next to the wells shown on the map (Appendix III). Contour lines were then drawn by connecting the points of equal groundwater level. The drawdown caused by the production wells F1 to F9 when they were in operation (indicated by a black spot on the map) was not taken into account, for the drawdown caused by pumping is only of local extent and does not affect the groundwater level in the observation wells situated a few metres away from the production well (eg pumping well F1 and observation well 311).

The shapes of the piezometric surfaces/water tables for the higher and lower groundwater levels revealed by the groundwater contour-maps for

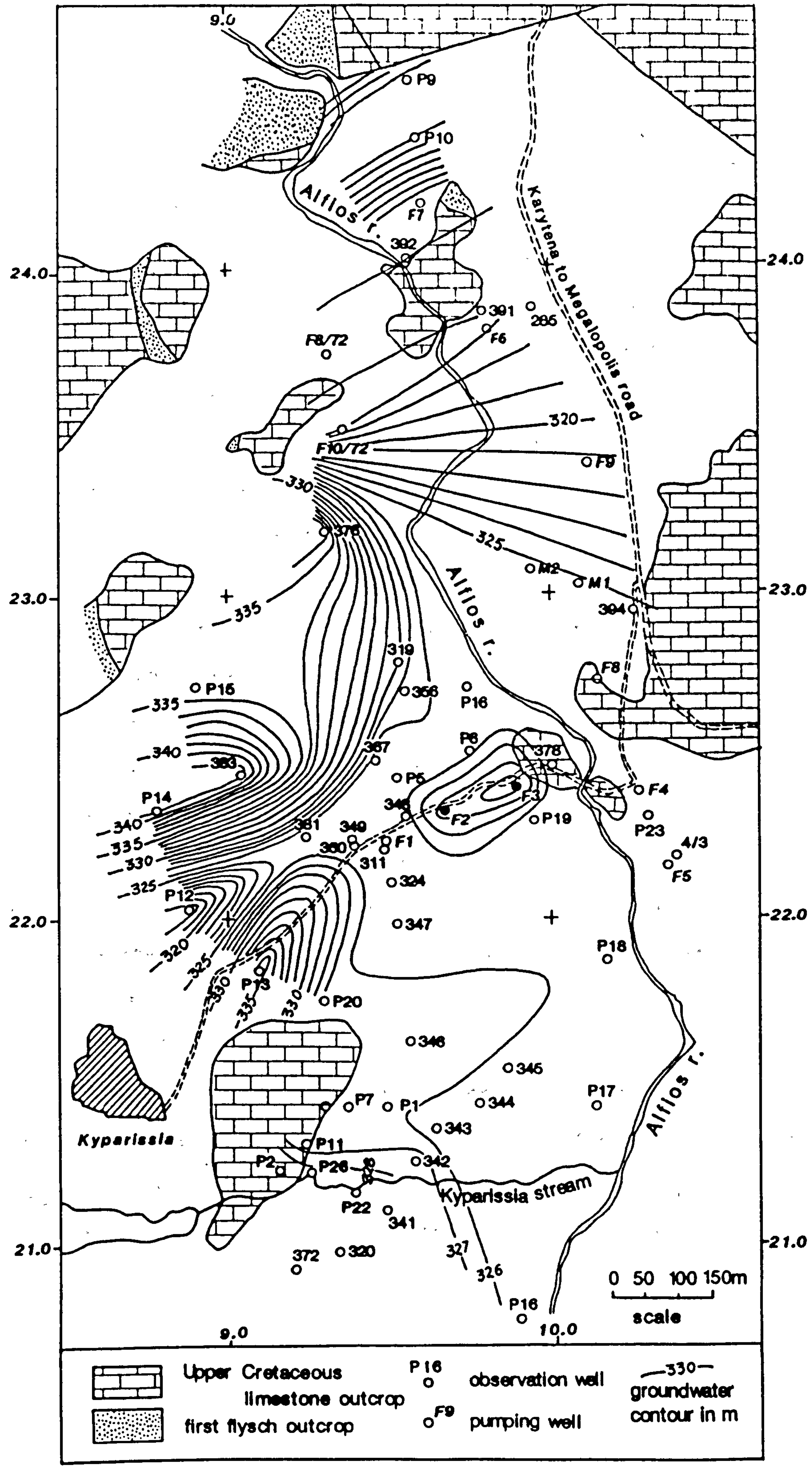


Fig 11.6 Map of the hydraulic head distribution in the karstic aquifers developed in the Kyparissia area; lower groundwater levels recorded on 13/11/77.

the period 1977-81 are characteristic of the hydrogeological regime of the area. They show alternating areas with planar and very steep groundwater levels. In places (ie 11 May 1980) a great difference of up to 32.7 m in the groundwater level existed between the adjacent wells P12 and P14, situated less than 300 m away from each other.

According to Darcy's law, $Q = Aik$, where Q equals the quantity of water flowing between two points, i equals the hydraulic gradient existing between them and k represents the permeability coefficient of the porous medium. As only minimal groundwater movement takes place within the basin, those zones along which a steep slope of the groundwater levels occurs (ie along which a high hydraulic gradient (i-value) exists) must have a low k-value which shows the presence of low permeability/aquiclude rocks along these zones.

These hydrogeologically determined zones of impermeable rocks, which act as barriers to the groundwater movement, coincide with those zones of first flysch whose presence has been inferred both geologically and geophysically. In Figure 11.8, which shows the position of the karstic aquifers developed in the vicinity of the Kyparissia field, these zones are represented by the first flysch bands defining the extent of the individual karstic aquifers.

The groundwater contour maps of the lower and higher levels of aquifers 1 and 2 will be given in Chapter 12 where these aquifers are discussed. It is not possible to draw such maps for the other aquifers (3 to 6) due to the restricted number of observation wells and hence of points for the recording of the groundwater level existing in each one of them.

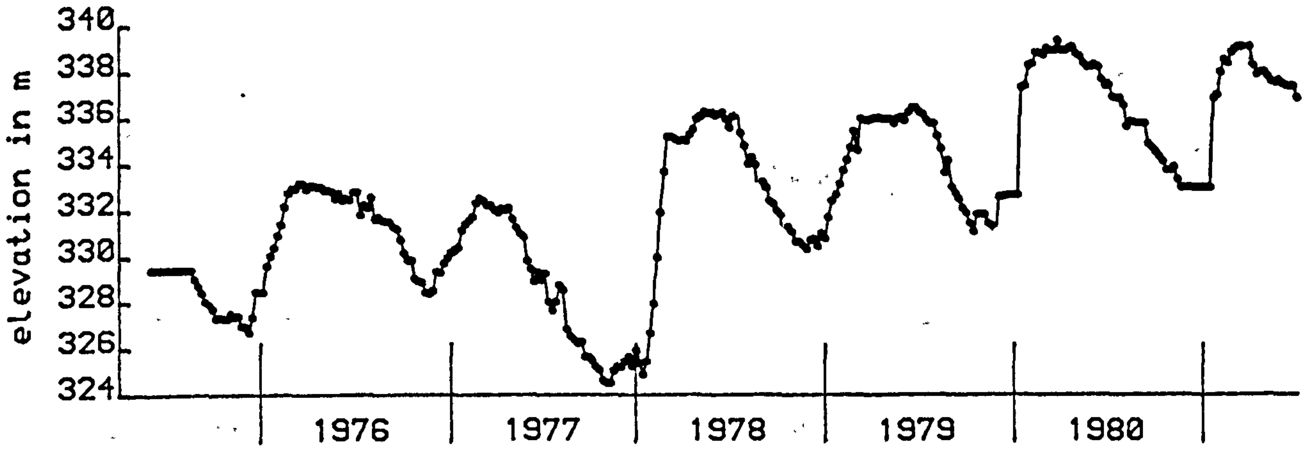
11.4.4.3 <u>Fluctuations of the groundwater level with time</u>

Well hydrographs were drawn for each of the observation wells. The groundwater level (in m above sea-level) was plotted against time (in weeks) using a computer.

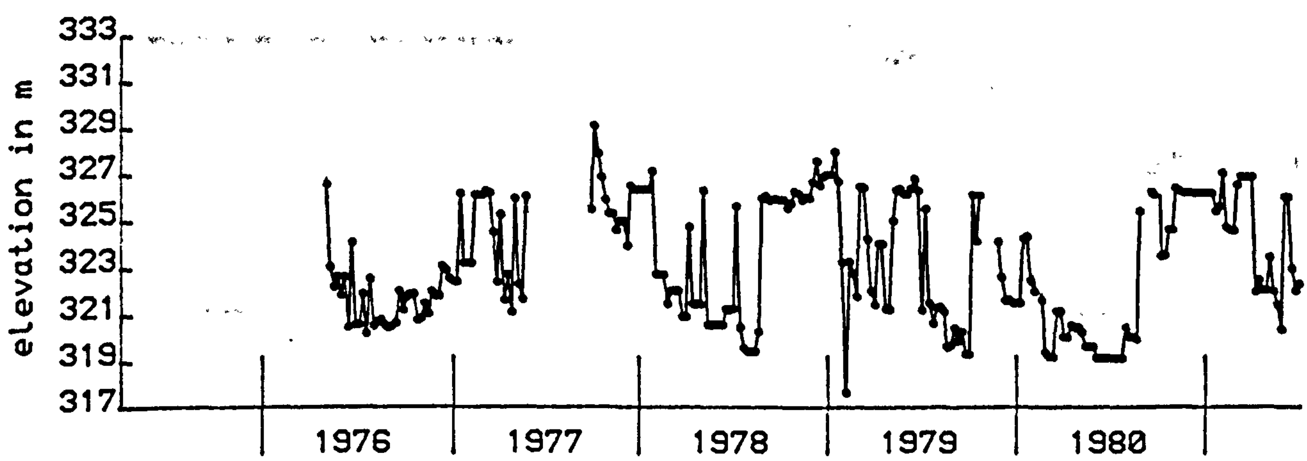
The study of the well hydrographs led to their division into five groups, based on the type of fluctuations shown by the groundwater level and also on the mean value of the hydraulic head recorded. An identical pattern of fluctuation in the groundwater levels was seen throughout the period of observation in each of the observation wells within any one group. These five groups of wells must, therefore, represent a corresponding number of individual, hydrogeologically isolated karstic aquifers. A representative well hydrograph for each of the five aquifers/groups of wells is given in Figure 11.6 and 11.7. The well hydrographs of all the wells used for this division will be given in Chapter 12, when each aquifer is studied and discussed in detail.

It should be noted here that when the recorded values for each well were plotted, in several cases one or more adjacent values departed greatly (in the range of a few metres) from the next or previous values recorded for that well. In general, corresponding discrepancies were not reflected in the values recorded in the other wells of the group at the same time. These values were, therefore, considered to be erroneous and were, in a few cases, discarded.

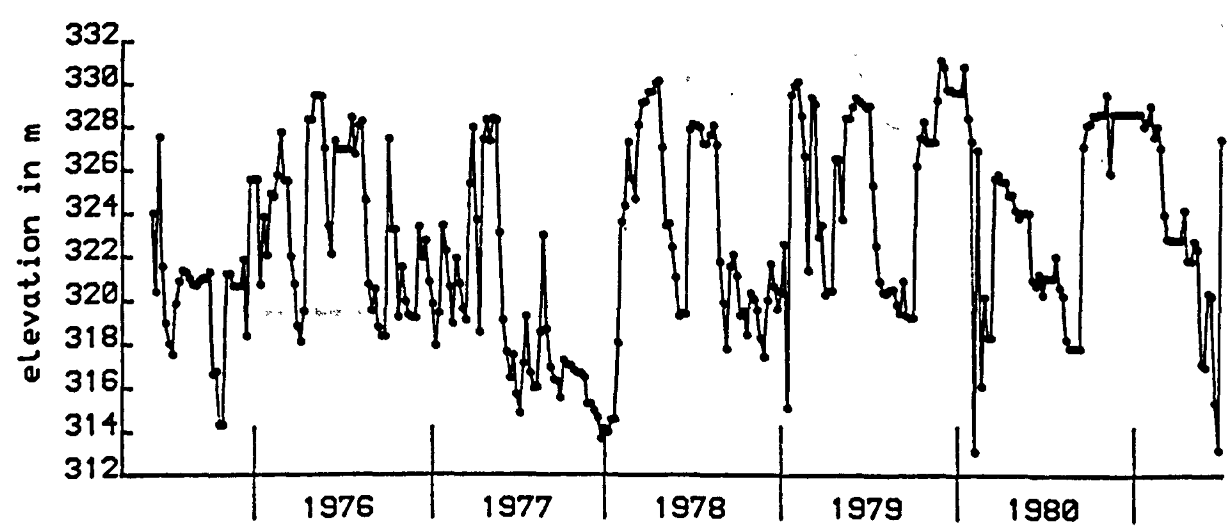
The Kyparissia field and the area surrounding it were also divided into corresponding separate aquifers, their extent having been determined according to the distribution of each group of wells (Fig 11.8). For this separation, the extent of the limestone subcrops in the Kyparissia field was also taken into consideration.



a) Groundwater hydrograph of well 347, sunk in aquifer 1.

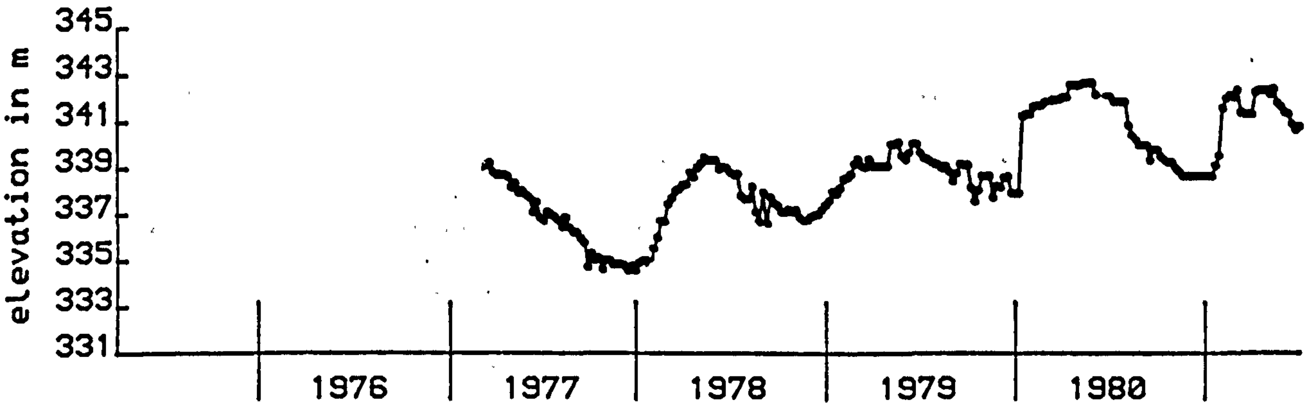


b) Groundwater hydrograph of well P10, sunk in aquifer 2/3.

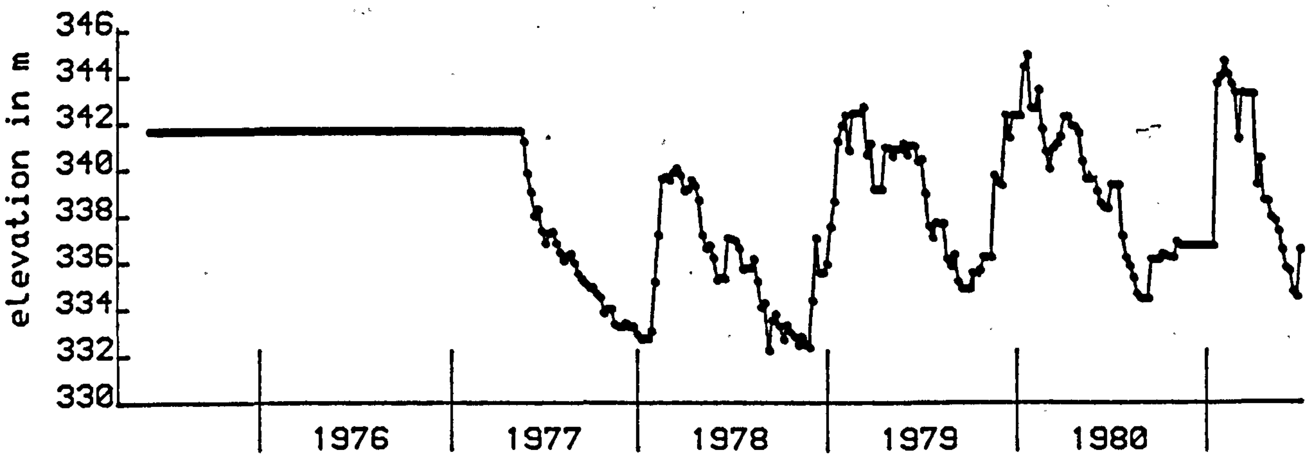


c) Groundwater hydrograph of well F10/72, sunk in aquifer 2/3.

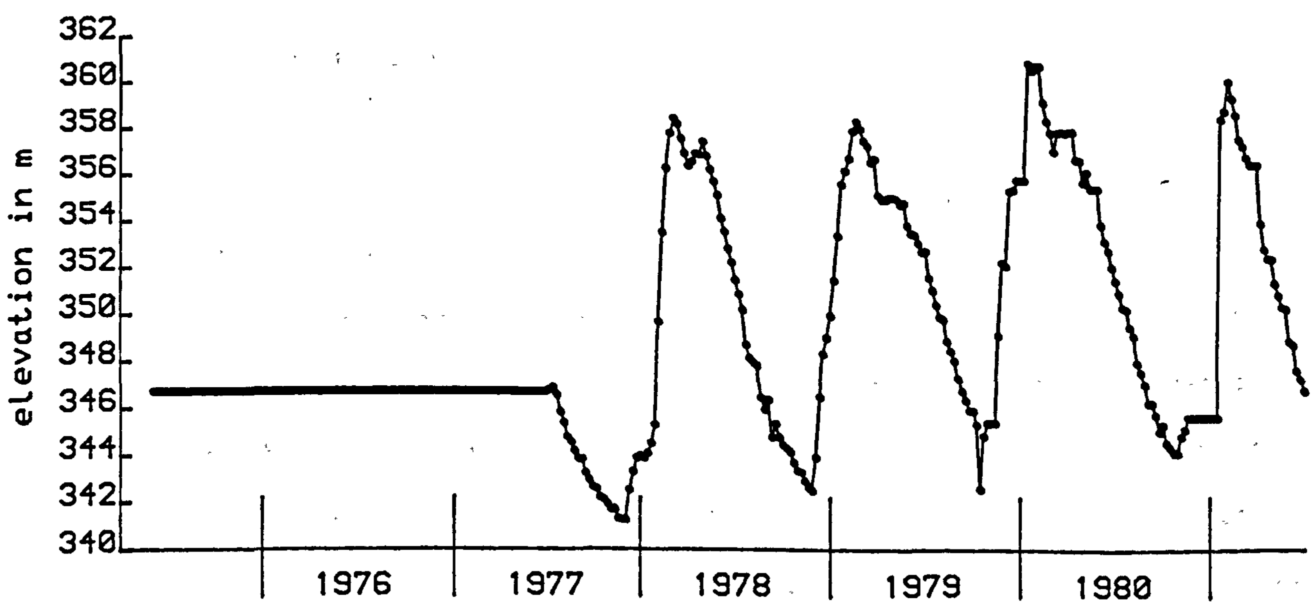
Fig 11.6 Representative groundwater hydrographs of the karstic aquifers 1 to 3 developed in the vicinity of the Kyparissia field.



a) Groundwater hydrograph of well P13, sunk in aquifer 4.



b) Groundwater hydrograph of well P15, sunk in aquifer 5.



c) Groundwater hydrograph of well P14, sunk in aquifer 6.

Fig 11.7 Representative groundwater hydrographs of the karstic aquifers 4 to 6 developed in the vicinity of the Kyparissia field.

11.4.4 Hydrochemical extent of the karstic aquifers

A detailed hydrochemical investigation was carried out during the present study as described in Chapter 12.

The chemical composition of the surface water (Alfios river), the water of the karstic springs emerging to the north of the Kyparissia field and the groundwater of aquifers 1 and 2 was studied.

The hydrochemical investigation established that these two aquifers, the main ones developed beneath the Kyparissia field, contain water of different chemical composition. Aquifer 1 contains water of $Ca/Mg:HCO_3$ type, while aquifer 2 contains water of $Ca/Mg:HCO_3/SO_4$ type. According to the existing hydraulic gradient between aquifers 1 and 2, water should move from the former to the latter. The difference in chemical composition of the water in these two aquifers could not, however, be explained as a natural process of evolution of the water chemistry and so the presence of these chemically different water types acts as proof that the two aquifers are not in hydraulic continuity but, rather, make up two separate hydrogeological units with different hydrogeological and hydrochemical regimes.

11.5 Conclusions

1) The terrace gravel-bodies of the Alfios river are, generally, highly permeable, although a lower degree of permeability must be assigned to the Thoknia and especially the Potamia terraces, due to the higher proportion of clay in their composition. Based on their lithology, parts of higher permeability must be present within them in the form of channels or lenses.

2) They form a single aquifer which is in close hydraulic relationship

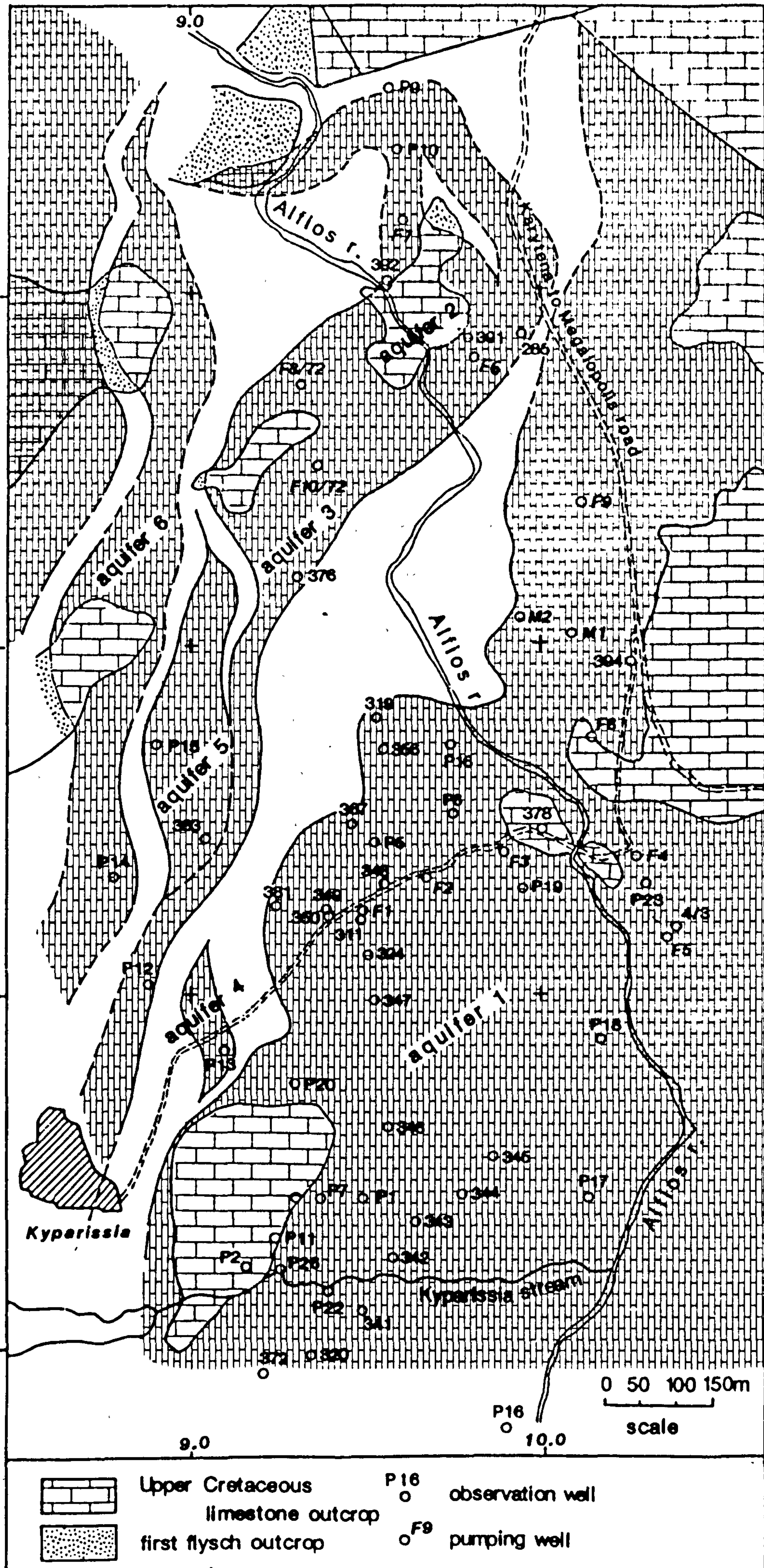


Fig 11.8 Extent and notation of the karstic aquifers developed in the Kyparissia area.

with the surface water system (eg Alfios river and minor tributaries) and also in places (eg around and to the north of the Kyparissia bridge over the Alfios river and at the Aghios Georgios gorge) with the karstic aquifers developed in the vicinity of the Kyparissia field.

3) A few aquifers of small extent and thickness are developed in the permeable parts of the unconsolidated basin sediments filling the Kyparissia field. These aquifers must occur as separate groundwater bodies, as different groundwater levels were recorded in a few of them. A few are, furthermore, under artesian (confined) conditions. The lignite beds are, in places (ie Sikalia ridge, Lapatou sub-basin), fragmentary (usually within their upper 20 metres) and relatively permeable. Finally, in the Sikalia ridge, where they lie directly on the limestone, the aquifer developed within them is in hydraulic continuity with the karstic aquifers.

4) The study of the geology and hydrogeology of the Kyparissia field revealed the presence of five separate karstic aquifers developed in the Upper Cretaceous limestone bedrock, each having its own individual hydrogeological regime.

a) The geological study of the area indicated the possibility of the presence of a thrust-slice structure beneath at least part of the Kyparissia field and a few thrust-slices were, in fact, distinguished as individual units in the central and western parts of the Kyparissia field. It is possible that the Upper Cretaceous limestone parts of each one of these thrust-slices may form an individual hydrogeological unit.

b) The hydraulic head distribution as it recorded in the observation wells sunk into the karstic aquifers developed in the vicinity of the Kyparissia field, the pattern of fluctuations of the groundwater level during the period 1975-81 and the results of the hydrochemical investigation all confirmed the existence of the various limestone subcrops-karstic bodies as individual isolated hydrogeological units.

CHAPTER 12: FLOW CHARACTERISTICS AND HYDRAULIC PROPERTIES OF THE KARSTIC AQUIFERS OF THE KYPARISSIA FIELD

12.1 Aquifer No 1

12.1.1 Introduction

Aquifer 1 is the largest of the karstic aquifers developed in the vicinity of the Kyparissia field. It occupies the central, eastern and southern parts of the field (Fig 11.8).

Its western extent is relatively well defined. It coincides with a line running in a NNE direction from west of the limestone hill outcropping next to the village of Kyparissia up to the east of the limestone outcrop at the Aghios Georgios gorge and then in a NNW direction up to the west of the limestone hill located to the north of the Panagia spring. Its northern extent is limited by a fault which also determines the northern extent of the limestone outcrop occurring next to the Panagia spring.

The eastern boundary of the aquifer cannot be clearly determined. Hydrogeologically, from the interpretation of the occurrence of the karstic spring situated in the northern part of the Megalopolis basin (Section 10.5) and the analysis of the data from the pumping tests (Section 12.1.5.3), it was concluded that the eastern boundary does not coincide with the eastwards extent of the Upper Cretaceous limestones and that it is much more likely that it terminates at a fault zone relatively close to the eastern boundary of the Kyparissia field, which brings these limestones into hydraulic continuity with the carbonate rocks of the Tripolis zone. The eastwards extent of aquifer 1 could only be accurately defined by the results obtained from boreholes sunk further east.

All the previous investigators considered all the Upper Cretaceous limestones outcropping to the east, to the north-east and to the north of the Kyparissia field (up to the water divide which borders the Lousios river up to the village of Stemnitsa) to be hydrogeologically associated with aquifer 1 and to form its catchment area. According to their calculations, the karstic aquifer extends over an area of about 170 km^2, of which 100 km^2 is made up of karstic limestones covered by basin sediments (Section 11.4.1.1).

Aquifer 1 is confined in the area of the Kyparissia field mostly by the relatively impermeable basin sediments (ie the Apiditsa stage and mainly the Marathousa beds). The extent of the confined areas depends on the hydraulic head in the aquifer at any given time and is, therefore, prone to extreme change, due to the fact that the upper surface of the aquifer exhibits a high morphological relief. The map of Figure 12.1 shows the areal extent of the confined and unconfined parts of aquifer 1. For the construction of this map, the piezometric surface in the confined part of the aquifer was taken as being at an elevation of 330 m, a level commonly recorded at the end of the dry seasons during the observation period.

12.1.2 <u>Sources of recharge</u>

The limestone of the karstic aquifer 1 is not exposed in the Kyparissia field. Over the wider area, except for a small occurrence next to the village of Kyparissia on the western side of the field, it outcrops predominantly on the eastern and north-eastern sides.

The eastward extent of aquifer 1, which also determines its catchment area, cannot be clearly defined. The hydrogeological investigations showed that aquifer 1 may be considered to be of limited

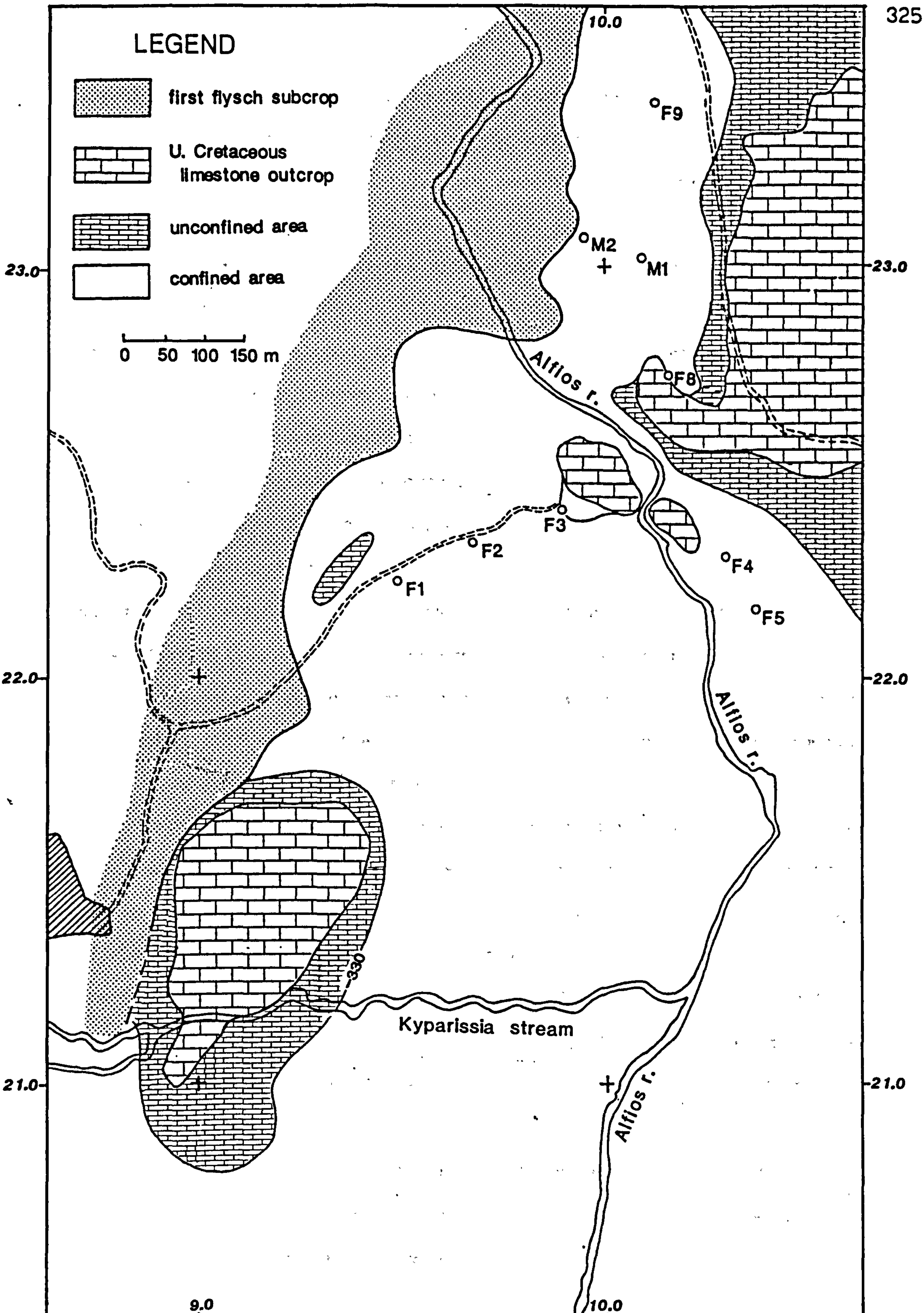


Fig 12.1 Confined and unconfined areas of the karstic aquifer 1.

extent, thus implying that the amount of water contributed to it through infiltrated precipitation must also be relatively small, although it should be noted here that it is not possible to determine the actual amount accurately.

The surface water from the Alfios river and the minor stream which flows to the south of the village of Kyparissia, together with the shallow aquifer developed in. the terrace gravel-bodies of the river, appear to be of much greater importance in the recharging of aquifer 1.

This minor stream flows to the south of the limestone hill next to the village of Kyparissia and crosses the limestone outcrop of aquifer 1 to the SE of the village, along a distance of less than 200 m. Data concerning its discharge do not exist. It is a relatively small winter stream which drains a small catchment (approximately 4.2 km^2) mainly of first flysch bedrock on the western side of the Kyparissia field. It starts to flow after the first rains in the autumn and dries up a short while after the end of the rainfall period (late spring-early summer). Its flow originates largely from direct run-off.

Water of this stream percolates into aquifer 1 during its entire flow period. This is clearly evident from the study of the contour maps of the higher and lower piezometric surfaces (Section 12.1.4.2) and also of the groundwater hydrographs of the wells situated around this area (Section 12.1.4.1). This stream crosses the limestone outcrop and enters aquifer 1 at an elevation of approximately 360 m, provided that the hydraulic head in aquifer 1 does not already exceed 340-345 m (Appendix III).

The hydrogeological relationship between aquifer 1 and the Alfios river, together with the aquifer developed in its terrace gravel-bodies, is, on the other hand, much more complicated.

The Alfios river runs to the eastern side of the Kyparissia field. For a small area south of and a larger area north of the Kyparissia bridge, the terrace gravel-bodies along the river directly overlie the limestones of aquifer 1 while, for a short distance, the Alfios river itself runs over the limestone outcropping below and around the Kyparissia bridge (Fig 12.2). The Alfios river flows in this area, in which it is in direct hydraulic continuity with aquifer 1, at an elevation of some 335 m at the highest point upstream and of approximately 333 m at the lowest point downstream.

As has already been noted in Section 11.2, the Alfios river and its associated tributaries are in close hydraulic relationship with the terrace gravel-bodies adjacent to their courses. Thus, during the wet season, water from the Alfios river is transmitted to the aquifer developed in the terrace gravel-bodies (influent conditions) while, during the dry season, groundwater from this aquifer is contributed to the Alfios river base-flow (effluent conditions).

The recent gravel body and the Lower terrace consist largely of gravels and sands and partly of clays and silts. The Thoknia terrace has a similar composition, although a considerably higher content of clays and silts is present locally. All these bodies are of high permeability, according to their lithological composition. Wells sunk in these bodies are of high productivity, flowing all the year round. The Potamia terrace generally contains an even higher proportion of clays and silts and only channels or lenses of good permeability exist within it.

The terrace gravel-bodies of the Alfios river are considered to comprise a unique hydrogeological unit. In places, due to the narrowing of the underlying impermeable strata (ie Marathousa beds), the water partly flows out of the terrace gravel-bodies and returns to the river

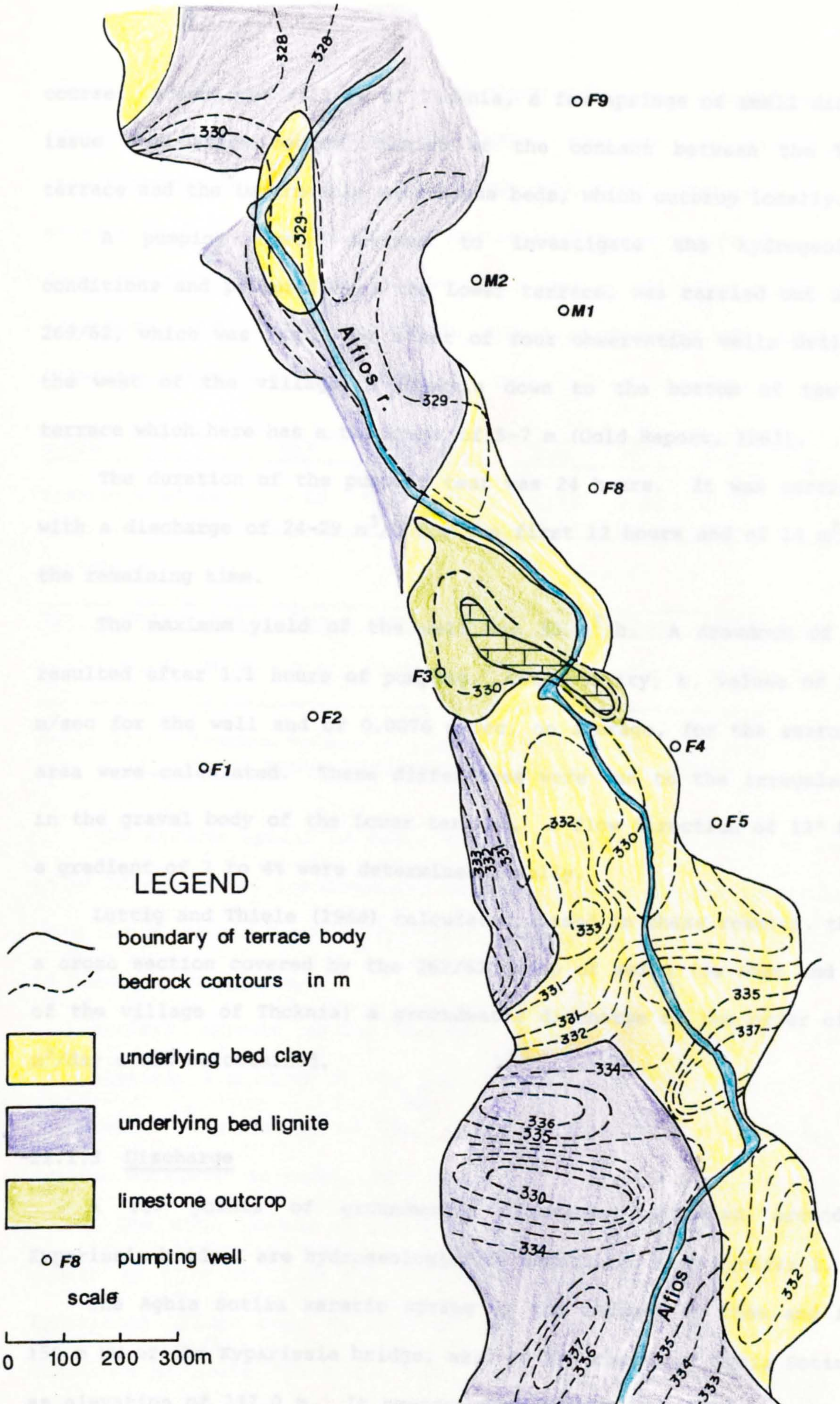


Fig 12.2 Geological map of the area around the Kyparissia bridge over the Alfios river, after Georgen, 1978.

course. Around the village of Thoknia, a few springs of small discharge issue from these bodies, almost at the contact between the Thoknia terrace and the impermeable Marathousa beds, which outcrop locally.

A pumping test, devised to investigate the hydrogeological conditions and properties of the Lower terrace, was carried out at well 269/62, which was framed by a set of four observation wells drilled to the west of the village of Thoknia down to the bottom of the Lower terrace which here has a thickness of 5-7 m (Gold Report, 1963).

The duration of the pumping test was 24 hours. It was carried out with a discharge of 24-29 m^3/h for the first 12 hours and of 14 m^3/h for the remaining time.

The maximum yield of the well was 33 m^3/h. A drawdown of 1.1 m resulted after 1.1 hours of pumping. Conductivity, k, values of 0.0121 m/sec for the well and of 0.0076 m/sec, on average, for the surrounding area were calculated. These differences were due to the irregularities in the gravel body of the Lower terrace. A flow direction of 12° NE and a gradient of 2 to 4% were determined locally.

Luttig and Thiele (1968) calculated, based on these results, that in a cross section covered by the 262/62 group of wells (ie west and south of the village of Thoknia) a groundwater discharge of the order of 2700 m^3/day could be obtained.

12.1.3 <u>Discharge</u>

A few points of groundwater discharge, situated around the Kyparissia bridge, are hydrogeologically associated with aquifer 1.

The Aghia Sotira karstic spring is the largest of them and issues 150 m NW of the Kyparissia bridge, near to the chapel of Aghia Sotira, at an elevation of 337.0 m. It emerges from within the limestone crevices, almost at the contact between the Upper Cretaceous limestone and the overlying impermeable Marathousa beds. The Aghia Sotira spring is intermittent. According to information from local inhabitants, it flows every 3 to 5 years and generally begins to flow no sooner than the first days of February. Only a few data are available concerning its discharge. The average or simple values of the sporadic measurements taken are given in Table 12.1.

month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
discharge m^3/sec	0.66	0.73	0.65	0.74	0.62	0.49	0.33	0.16

continued ..

Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
-	0.18	0.18	0.13	0.24	0.23	0.16	0.11	0.06	0.01

Table 12.1 Average values or simple values of the discharge of the Aghia Sotira spring (March 1963-August 1964).

The karstic spring of Aghia Sotira is considered to be an overflow point of aquifer 1, its discharge representing the surplus of groundwater when the hydraulic head in aquifer 1 exceeds the elevation of the point of issue of the spring.

Another karstic spring emerges through the limestone crevices, approximately 3 m north of the eastern pillar of the Kyparissia bridge. It flows at an elevation of 334.0 m. Its discharge is relatively small and was estimated in summer 1982 to be just a few litres per minute.

A few other points of discharge were described by the Gold Report (1963) to flow out from the limestones about 200 m north-east of the Kyparissia bridge over an area of about 500 m^2. They emerge at an elevation of about 340 m and their total discharge was measured to be 5 l/sec in mid-February 1962. Other similar small discharges are found on the eastern slope approach to the Kyparissia bridge (north and south of the road), at an elevation of 339.0 to 339.5 m.

According to local information, all these discharge points flow only in years with heavy rainfall and their flow lasts only for a short period in the late winter-mid spring.

Finally, a few other points of groundwater occur on the western ramp of the Kyparissia bridge to the south of the road, scattered over an area of about 200 m^2, at an elevation of approximately 338 m. These springs emerge at the contact between the impermeable Marathousa beds and the overlying Thoknia terrace gravel body, which wedges out at this point. It is assumed that these springs are fed from the aquifer developed in the terrace gravel bodies. Their total discharge during summer 1982 was considerably lower than that of the Aghia Sotira spring.

12.1.4 Groundwater levels

12.1.4.1 Well hydrographs

Forty-two water gauges were installed in aquifer 1 and were used to provide data for the water table level of this aquifer (see Fig 12.3). Nine of them (those numbered F1 to F5, F8 , F9, M1 and M2) are production wells. The first seven are utilised for water supply for the Electricity Power Station and have operated continuously since 1971, each at a rate of 300 m^3/h, possibly now slightly reduced due to their long-term operation. Pumping only stops in cases of breakdown or due to reduced needs of the Power Station. The remaining two wells (M1 and M2) supply the town of Megalopolis and each operates at a capacity of 100 m^3/h.

For each of these forty-two wells and observation boreholes, well hydrographs were drawn by plotting the elevation of the grounwater (in m

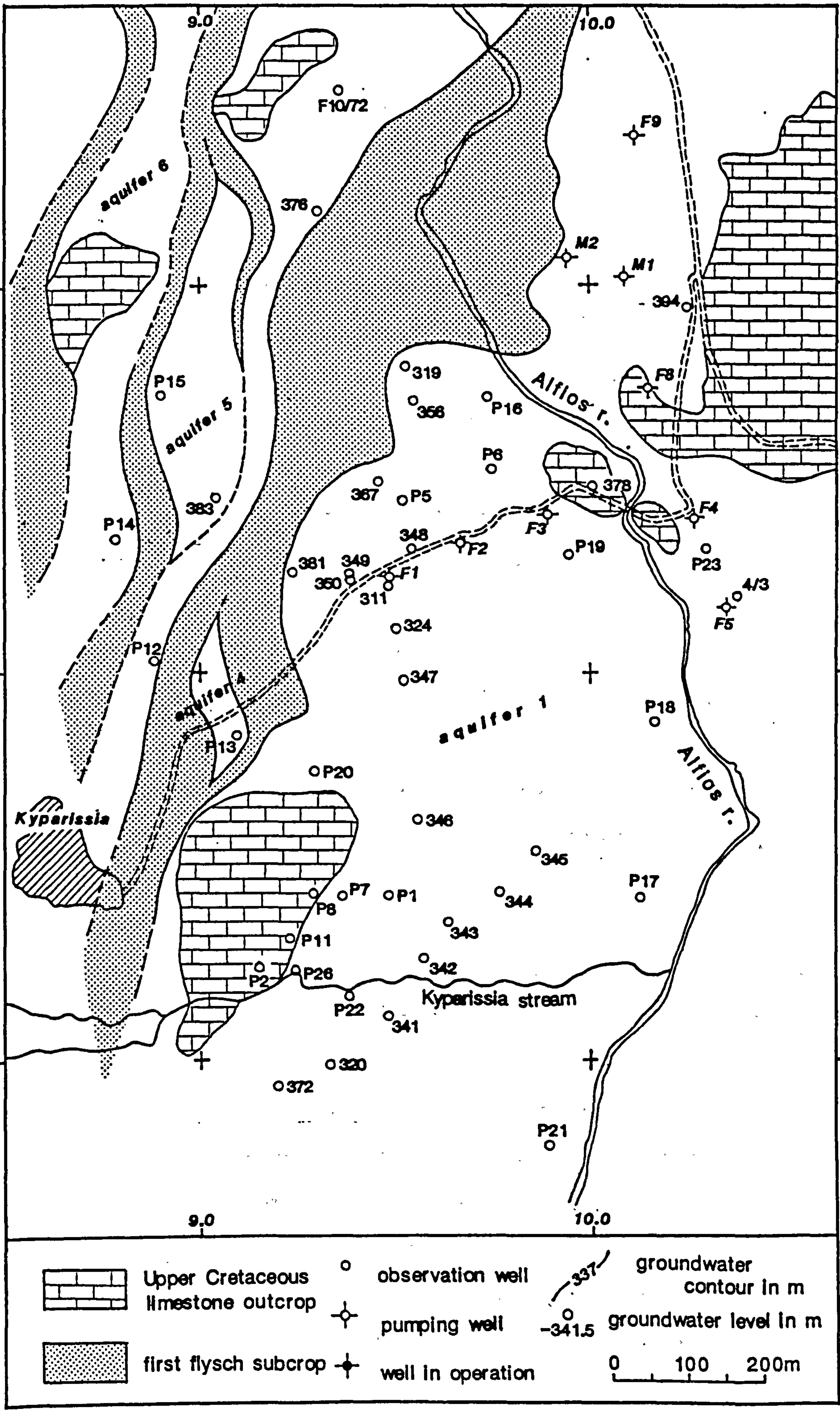


Fig 12.3 Location of the observation and production wells sunk in the karstic aquifers developed in the Kyparissia field.

above sea-level) against time (in weeks) for the observation period 1975-1981.

Study of these hydrographs revealed that the wells could be divided into three categories as follows:

A) The observation wells spread over the entire extent of aquifer 1, except for those belonging to the second category.

B) The observation wells situated on the south-western side of aquifer 1, south-east of the village of Kyparissia, on both sides of the Kyparissia stream, a minor tributary of the Alfios river.

C) The production wells situated on the central-eastern side of the wider area of the Kyparissia field, on both sides of the Alfios river.

Finally, well P9, situated on the far-northern part of aquifer 1, next to the Panagia spring presents a peculiar, almost flat hydrograph.

Wells within each of these categories of well hydrographs have common characteristics. Each category was individually studied.

Group A

The well hydrographs of this group, spread throughout the western extent of aquifer 1, that part coinciding with the wider area of the Kyparissia field (ie excluding both the wells situated on the south-western side of aquifer 1 and also the productive wells), present an almost identical pattern of fluctuations of groundwater level. Their hydrographs are shown in Figures 12.4 to 12.11.

Their striking feature is that they only present long-term fluctuations, ie seasonal and annual, while short-term fluctuations corresponding to heavy rainfalls, such as winter storms, are completely absent.

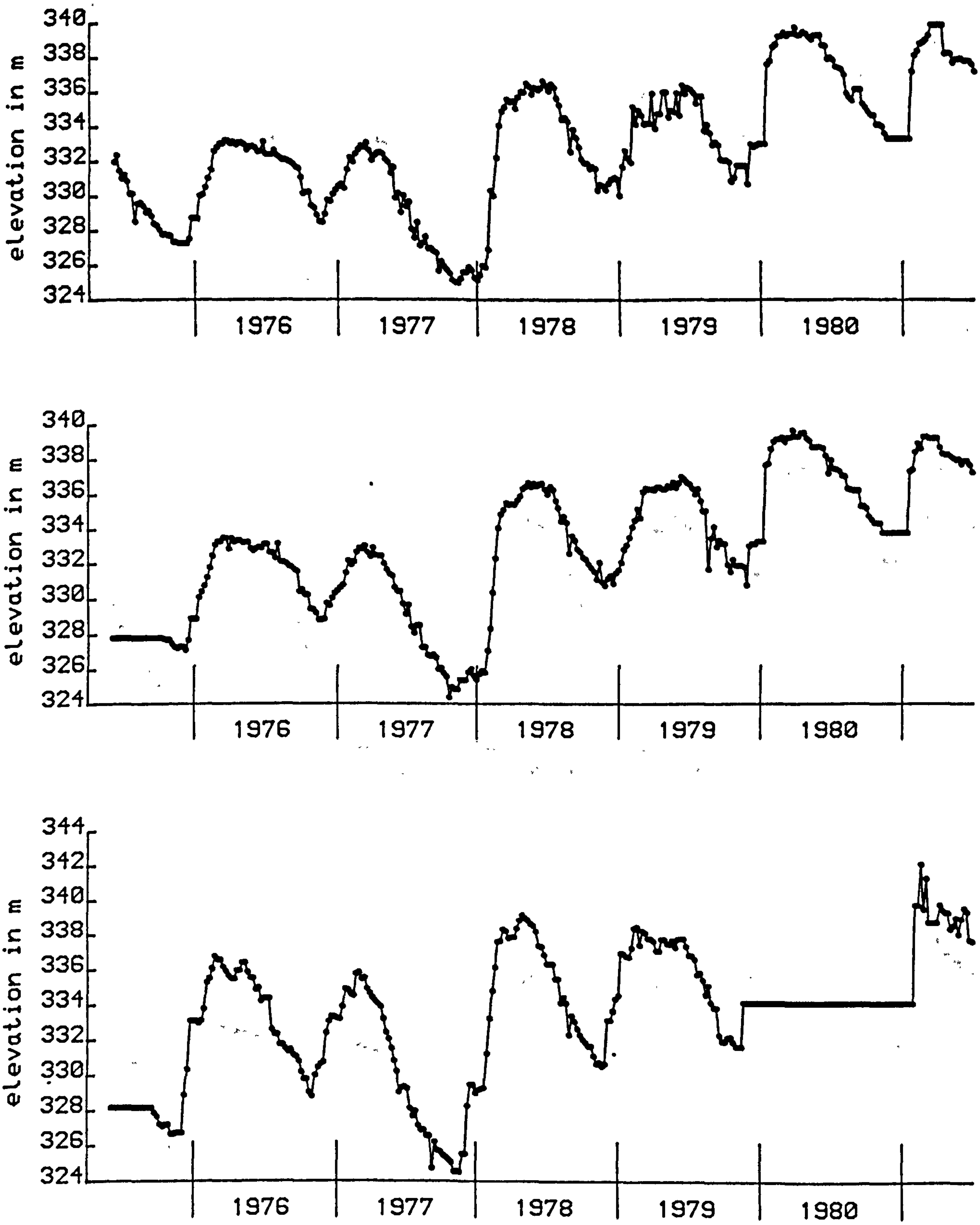
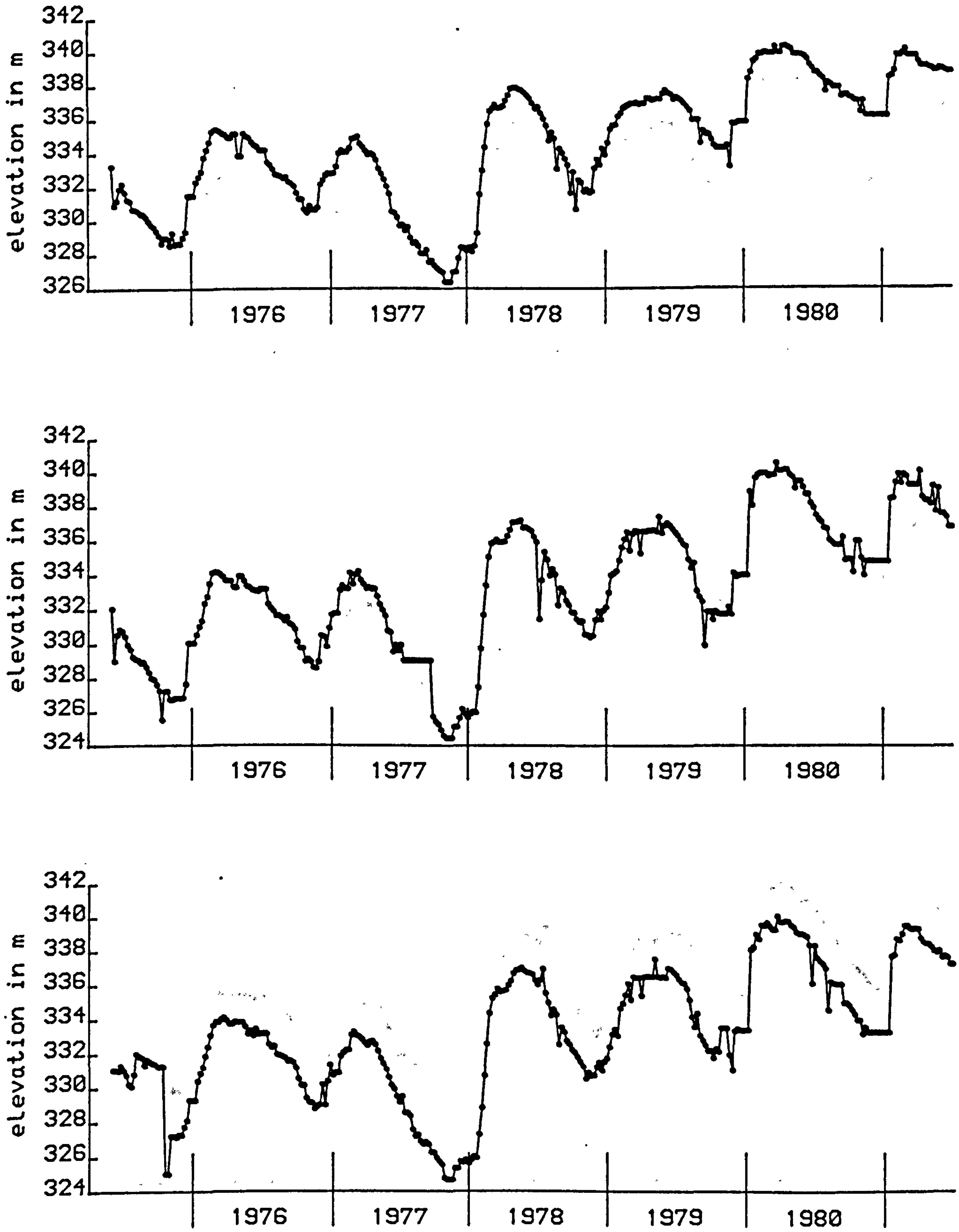


Fig 12.4 Hydrographs of the wells: a) 311, b) 324 and c) 341, sunk in aquifer 1.



12.5 Hydrographs of the wells: a) 342, b) 343 and c) 344, sunk in aquifer 1.

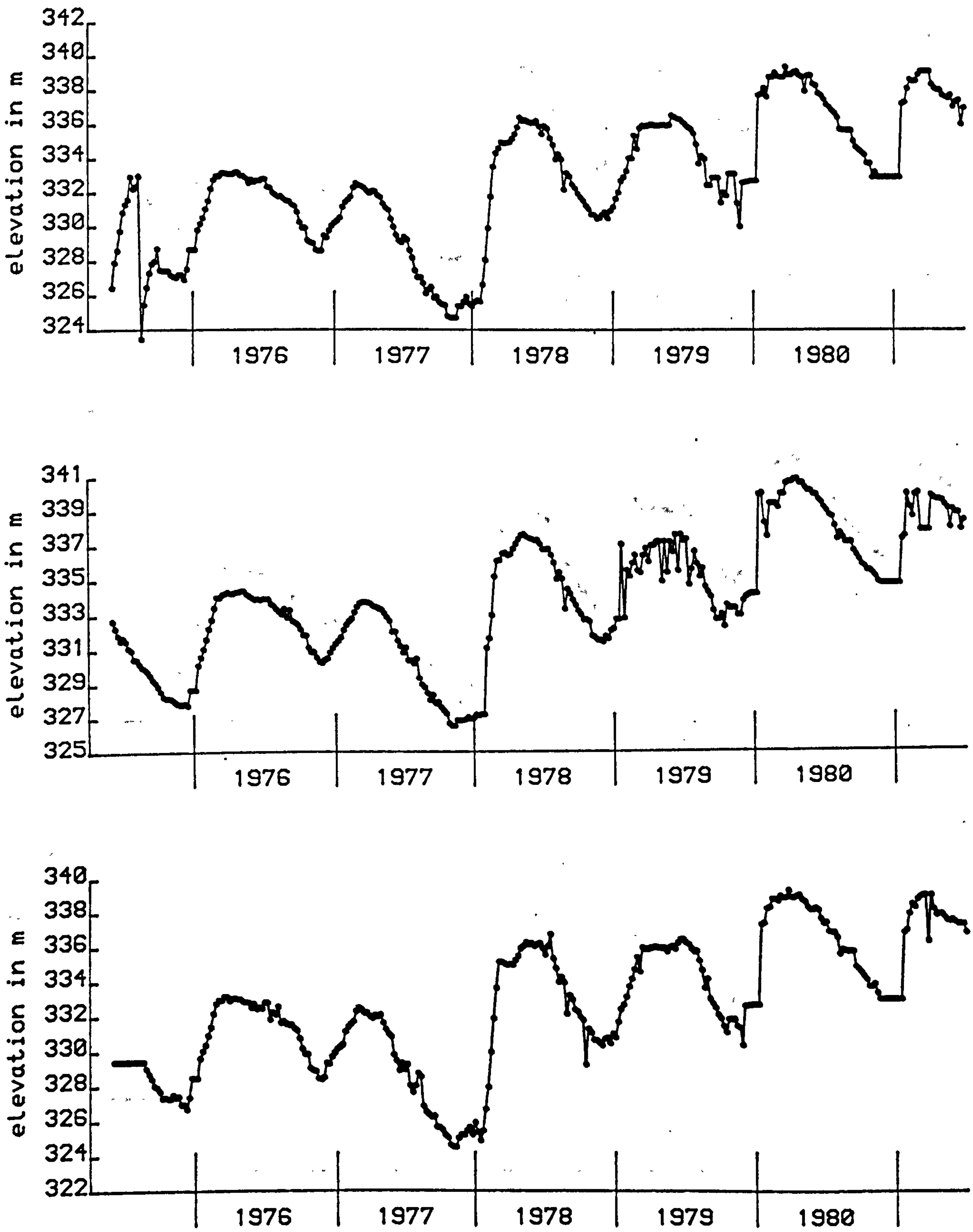


Fig 12.6 Hydrographs of the wells: a) 345, b) 346 and c) 347, sunk in aquifer 1.

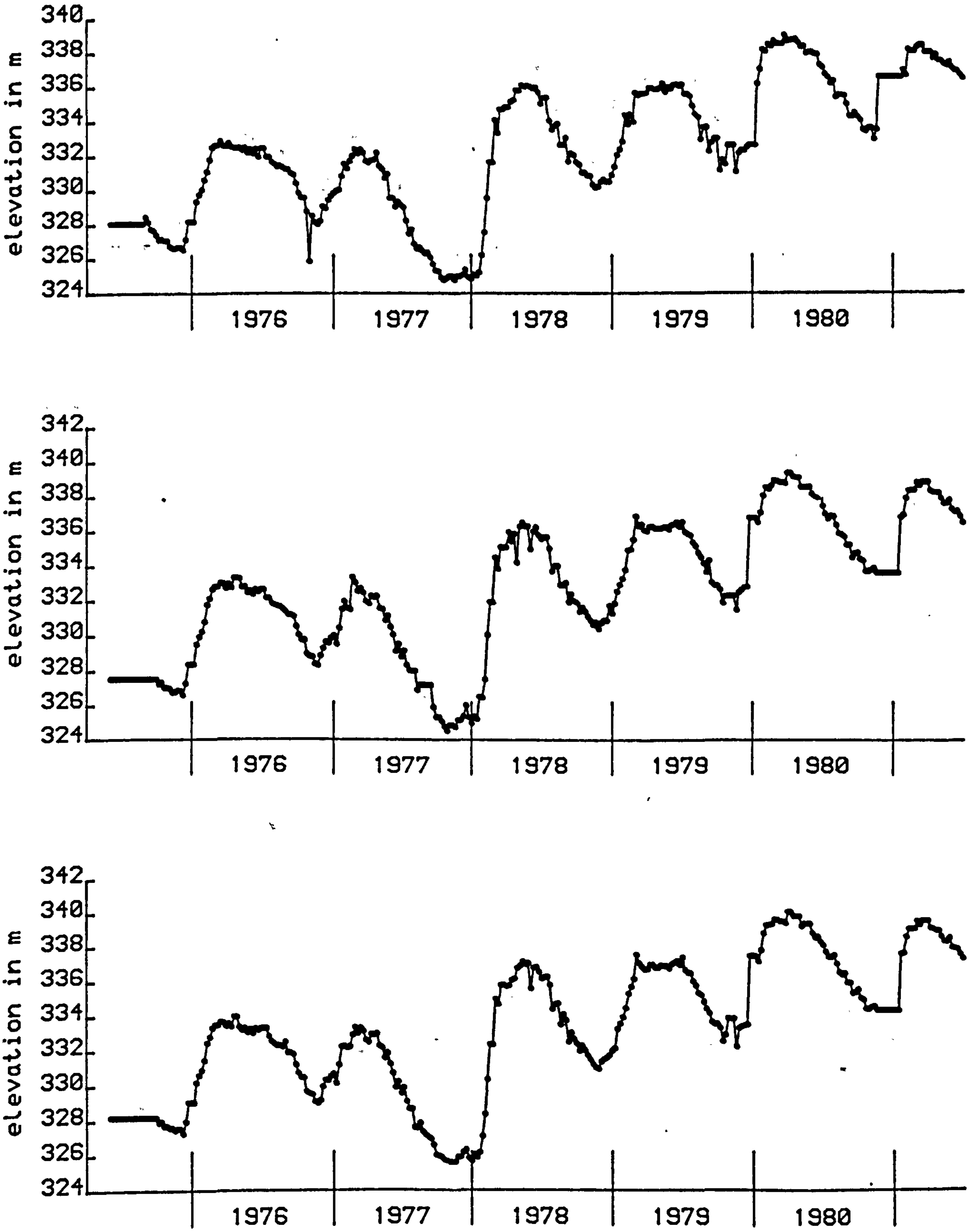


Fig 12.7 Hydrographs of the wells: a) 348, b) 349 and c) 350, sunk in aquifer 1.

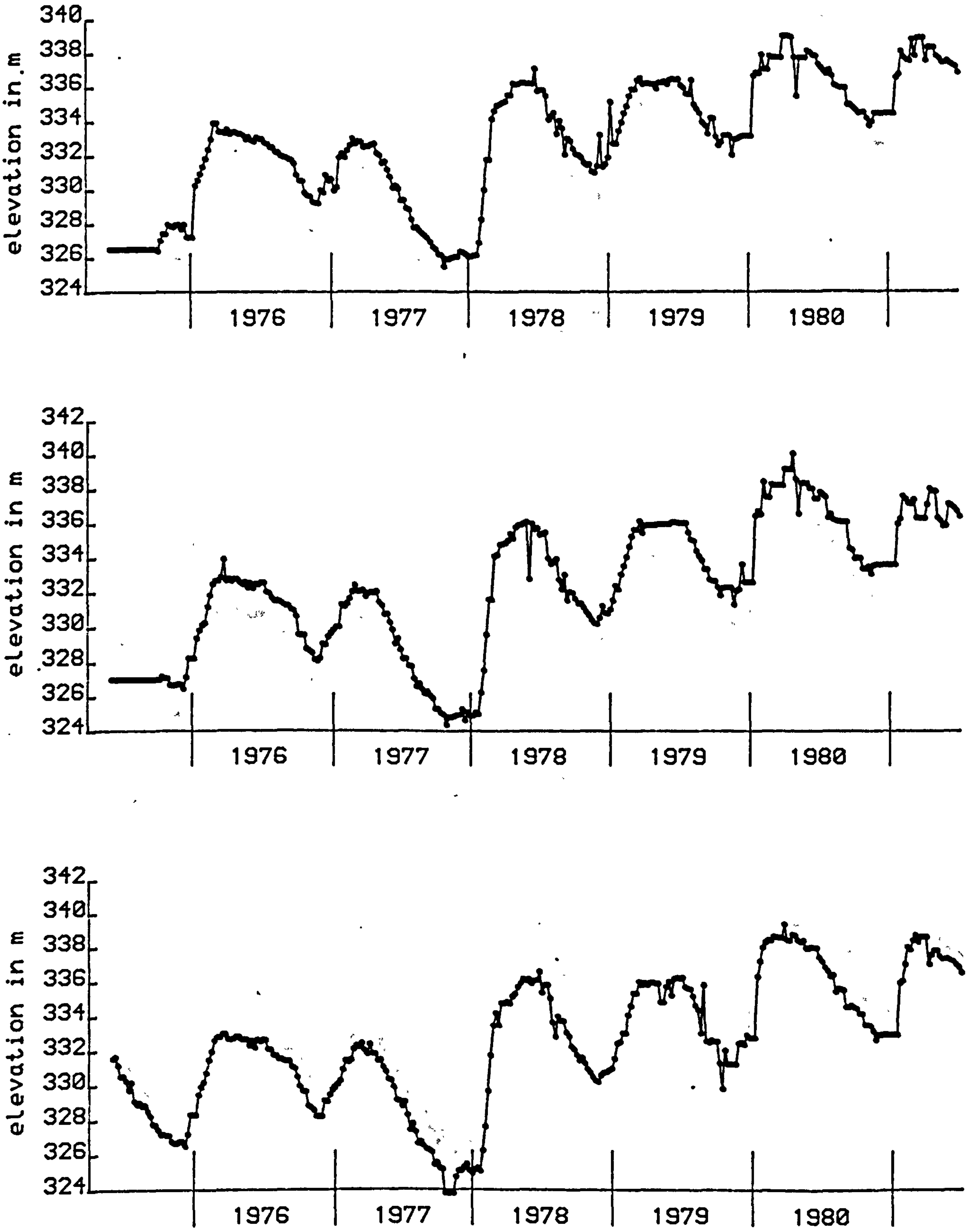


Fig 12.8 Hydrographs of the wells: a) 356, b) 367 and c) 378, sunk in aquifer 1.

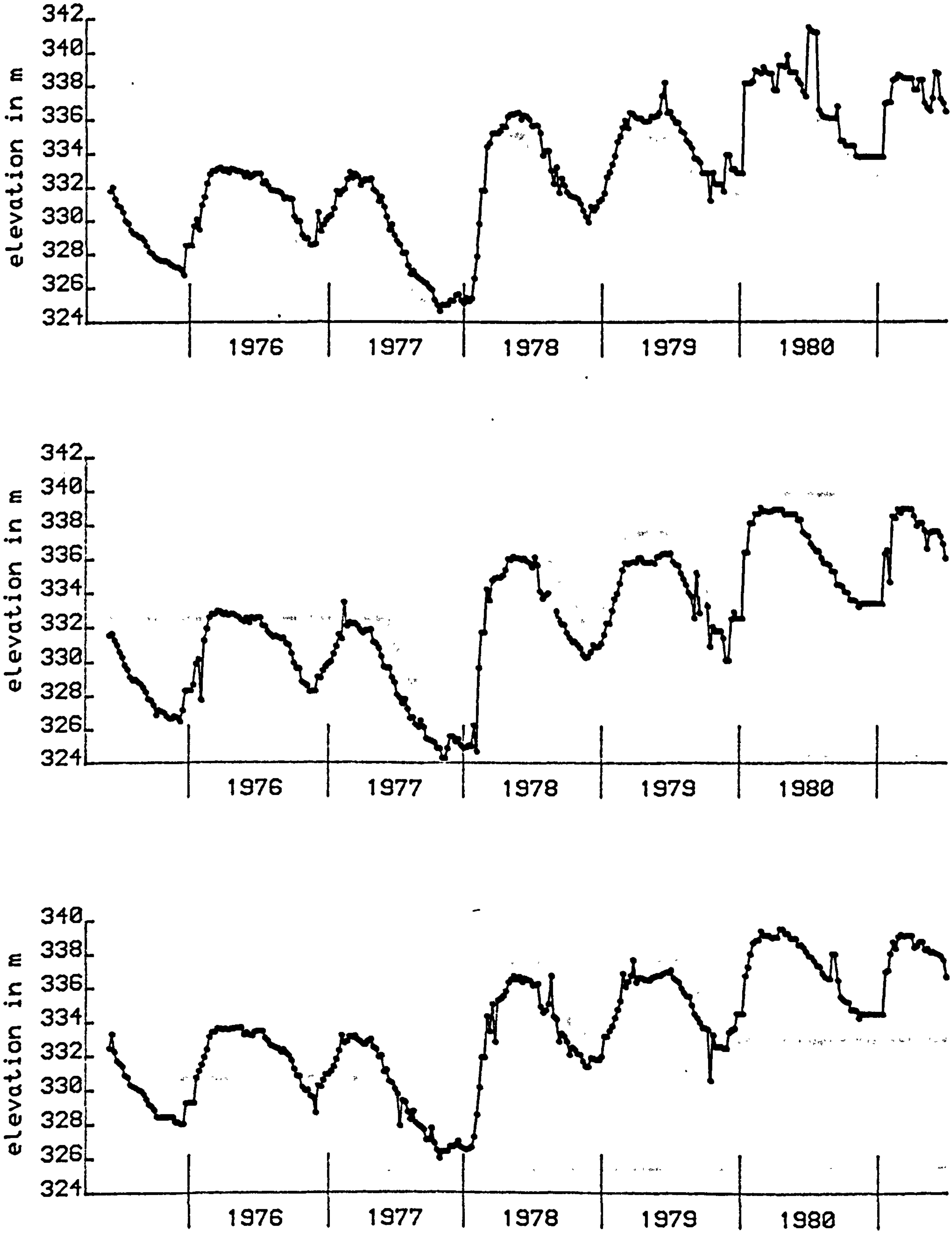


Fig 12.9 Hydrographs of the wells: a) 381, b) 394 and c) 4/3, sunk in aquifer 1.

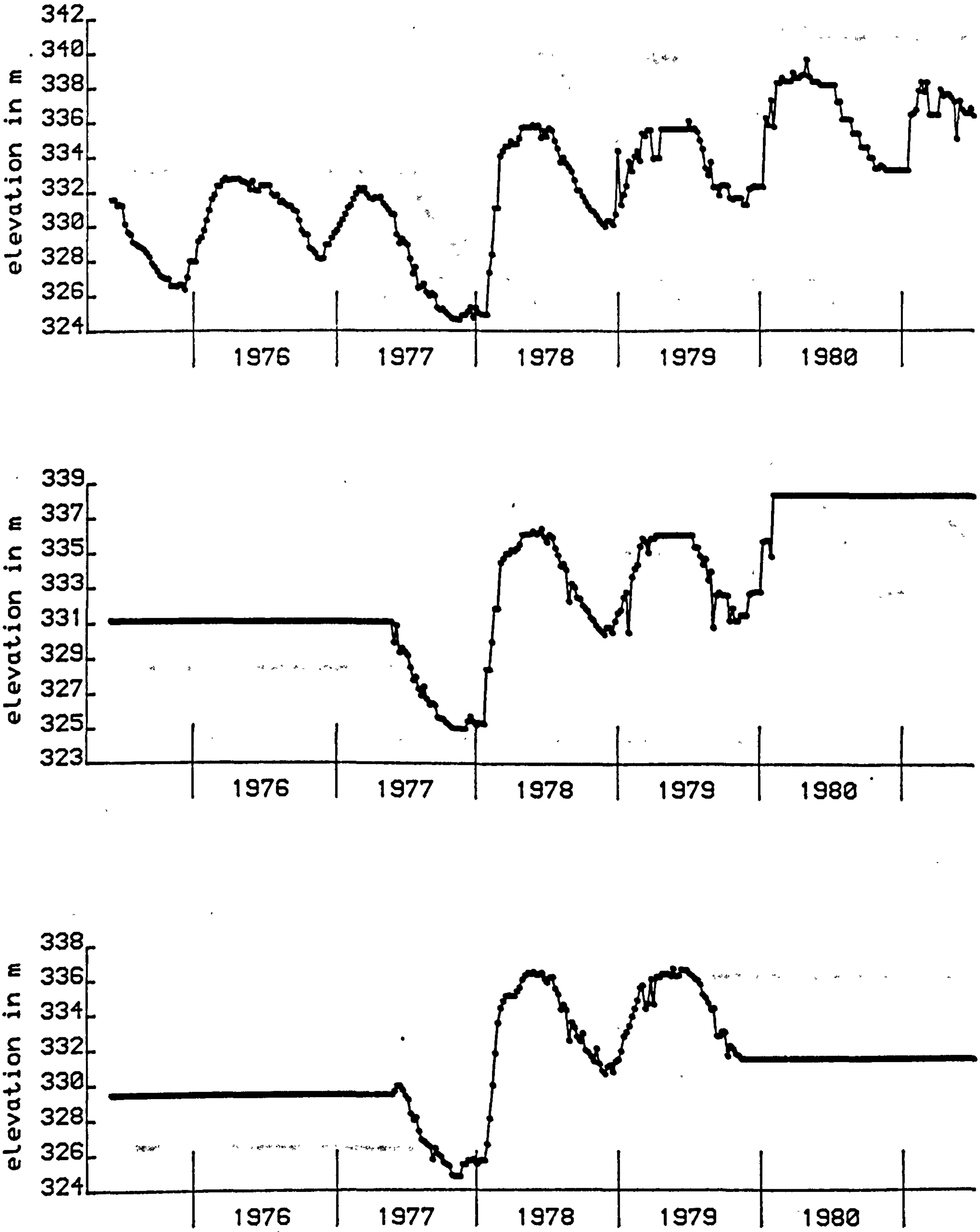


Fig 12.10 Hydrographs of the wells: a) P6, b) P16 and c) P17, sunk in aquifer 1.

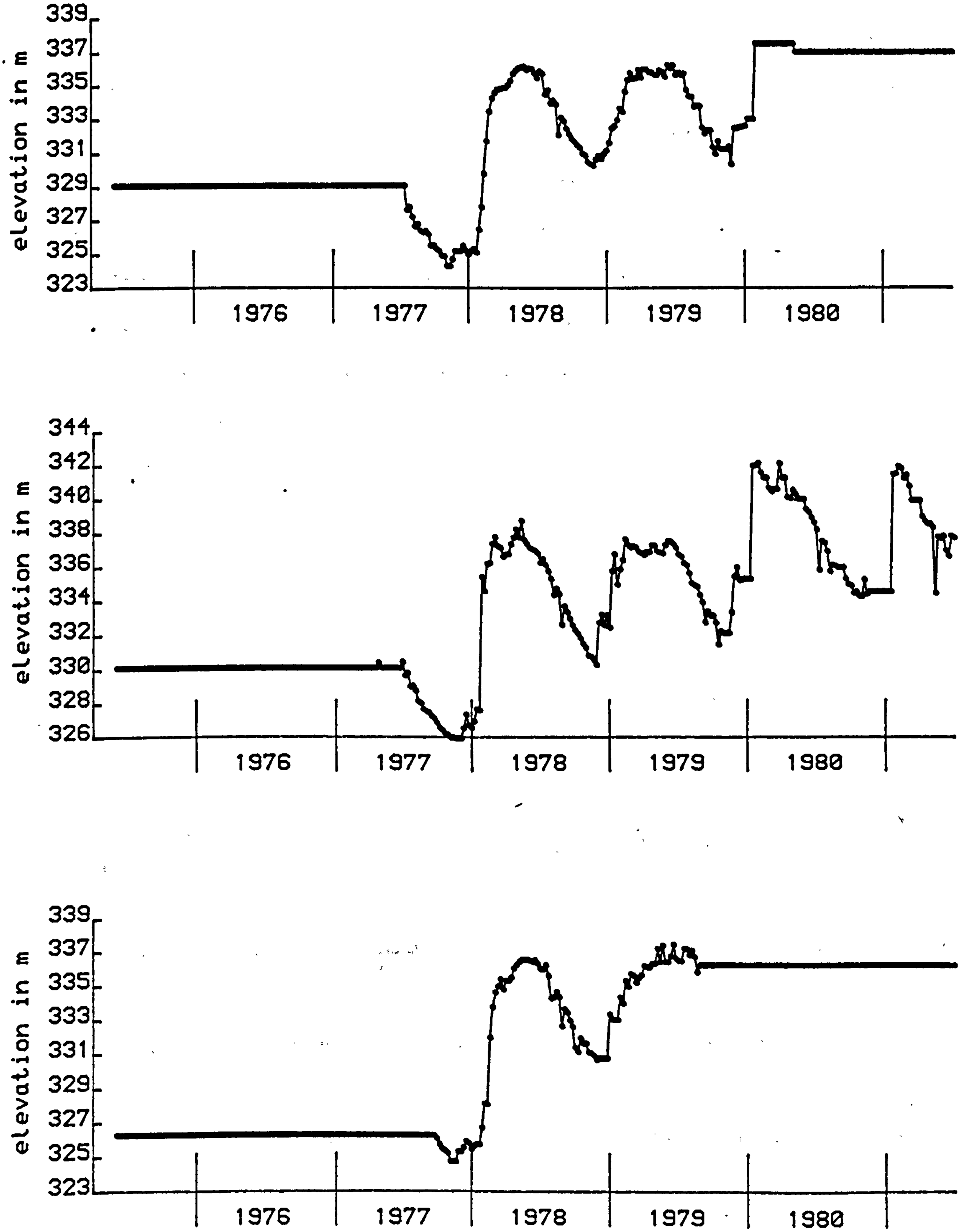


Fig 12.11 Hydrographs of the wells: a) P19, b) P20 and c) P21, sunk in aquifer 1.

Figure 12.12 shows the rainfall recorded at the station of Karytena which is the closest to the Kyparissia field. Data are plotted as weekly accumulated rainfall (in mm) against time (in weeks). It can be seen that, during the wet season of each year, there are periods of heavy rainfall of a few weeks' duration, interrupted by periods of a few weeks of low rainfall. When the rainfall graph (Fig 12.12) is compared with the well hydrographs it can be seen that there is no correlation between them, ie the hydrographs present no short-term fluctuations corresponding to and reflecting the precipitation regime (eg during the winter of 1977-78).

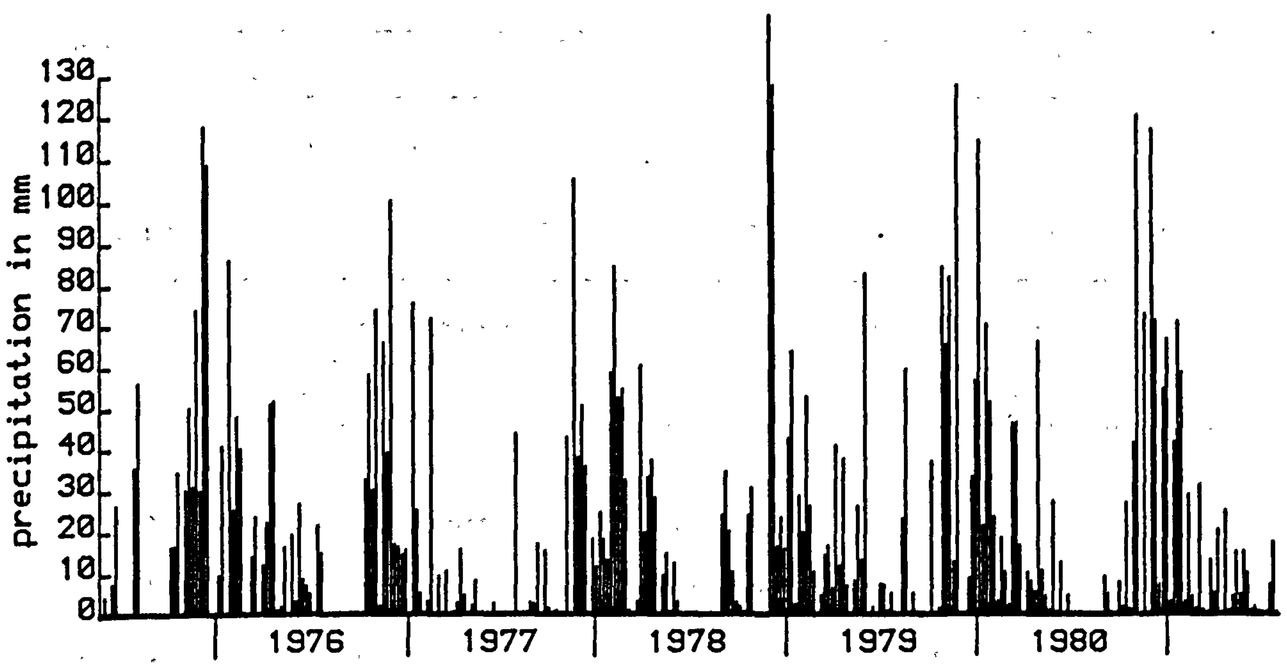


Fig 12.12 Weekly precipitation recorded at the Karytena station during the period June 1975-May 1981.

The well hydrographs show an almost continuous rise in the mean higher and lower groundwater levels in aquifer 1 recorded by means of the observation wells during the period of observation, despite the fact that, during this period, a continued high abstraction of water at a rate of more than 1,500 m^3/h was taking place.

Table 12.2 gives the recorded mean elevations of the higher and lower piezometric surfaces which occurred in aquifer 1 (Appendix III) and also the annual rainfall recorded at the Karytena station together with and that calculated for the whole of the Alfios catchment (Appendix Ic) for the corresponding years of the period of observation. The dates on which the lower and higher groundwater levels have been recorded in aquifer 1 are listed in Table 12.3

hydraulic head (m)	1975	1976	1977	1978	1979	1980	1981
higher	-	333-34	331-32	336-37	336-37	339-40	338-39
lower	327-28	329-30	325-26	331-32	332-33	334-35	-

annual rainfall (mm)	1974/75	1975/76	1976/77	1977/78	1978/79	1979/80	1980/81
Karytena station	854	1100	789	1070	1012	1091	990
Over the Alfios catchment	881	1173	931	1217	1198	1390	1375

Table 12.2 Mean elevations of the higher and lower groundwater levels (m above sea-level) in aquifer 1 and annual rainfall, recorded at the Karytena station and calculated for the whole of the Alfios catchment, for the corresponding years.

A rise of approximately 1 m each year occurs on average in the elevation of the higher and lower groundwater levels, although, in some years, only a small rise or even a decline in the elevation of the groundwater levels took place. This was due to a corresponding, rather continuous increase in mean annual rainfall over the whole basin during the respective years (Table 12.2).

Georgen (1978), after drawing maps of the higher piezometric surfaces during June 1963 and February/March 1976 and of the lower piezometric surfaces during November 1964 and November 1976, noticed that a minor pressure relief, of approximately 6.0 m in the higher pressure head and of approximately 4-5 m in the lower pressure head, took place during this period (see hydrograph of Fig 12.13a). He attributed this

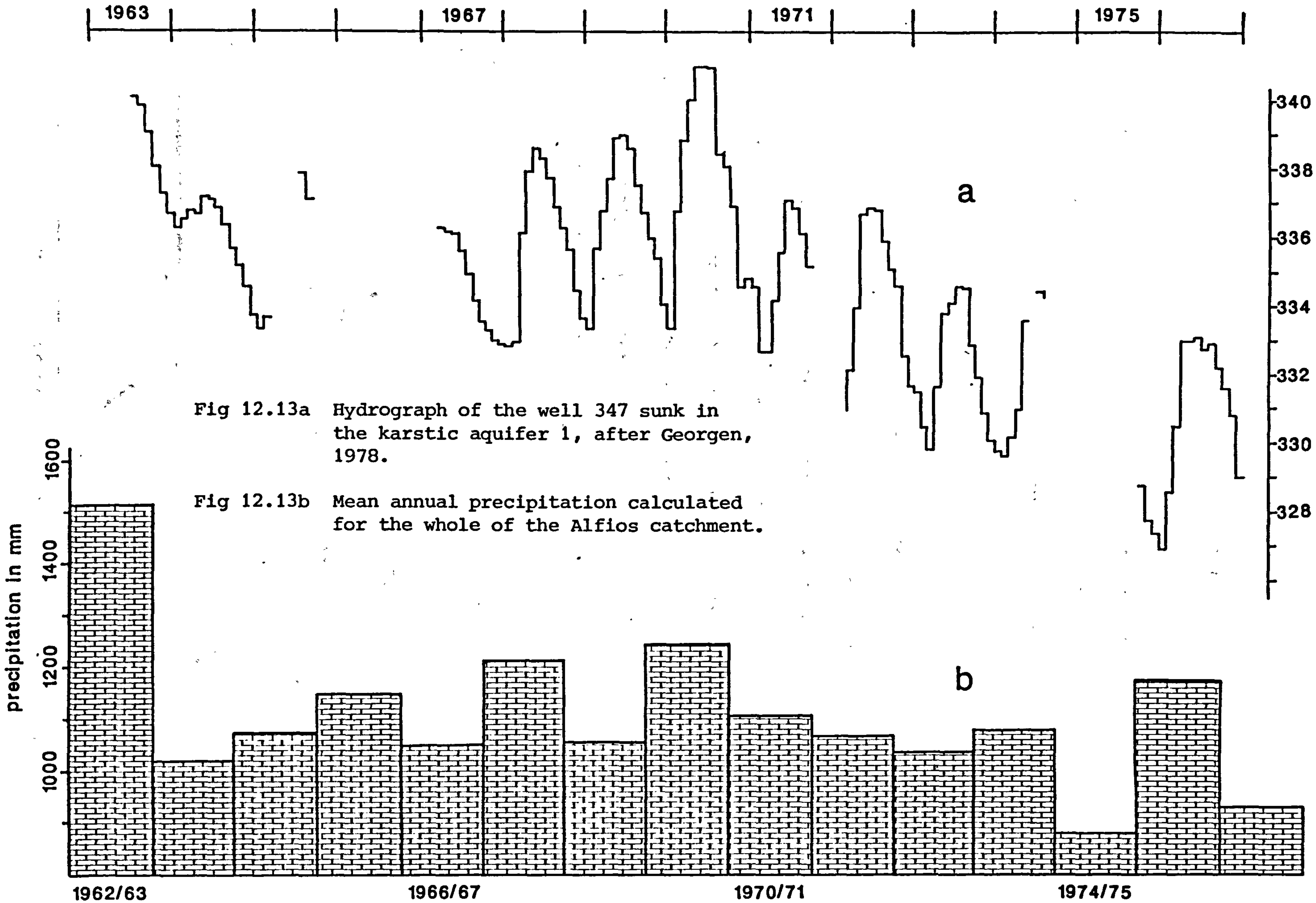


Fig 12.13a Hydrograph of the well 347 sunk in the karstic aquifer 1, after Georgen, 1978.

Fig 12.13b Mean annual precipitation calculated for the whole of the Alfios catchment.

decline in the elevation of the groundwater levels to the effect of the continuous abstraction of water from aquifer 1 by the power plant wells over five to six years of operation. Furthermore, he noticed that such a pressure drop was not observed from 1963 until 1970, corresponding to the time preceding the start-up of the power plant wells.

In fact, this decline noticed in the groundwater levels is due to a decrease in the total precipitation during the corresponding period (Fig 12.13b).

Group B

The second category comprises the hydrographs of the wells P1, P2, P7, P8, P11, P20 and 320. All these wells are situated on the south-western side of aquifer 1, to the south-east of the village of Kyparissia (Fig 12.3). Most are situated along the eastern side of the limestone hill here and the groundwater levels recorded in them therefore correspond to the water table fluctuations in the unconfined part of the aquifer. Only the water in wells P1 and 320 is under confined conditions. The hydrographs of these wells are given in Figures 12.14 to 12.16.

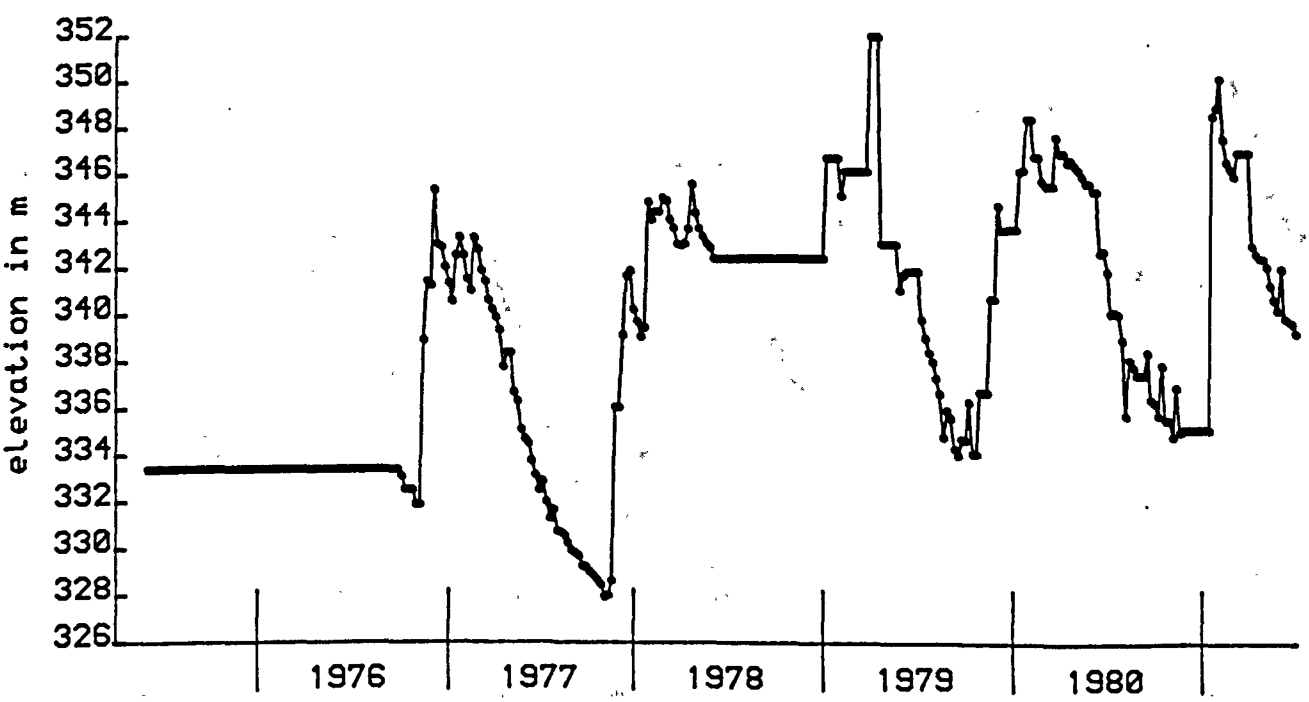


Fig 12.14 Hydrograph of the wells P2, sunk in aquifer 1.

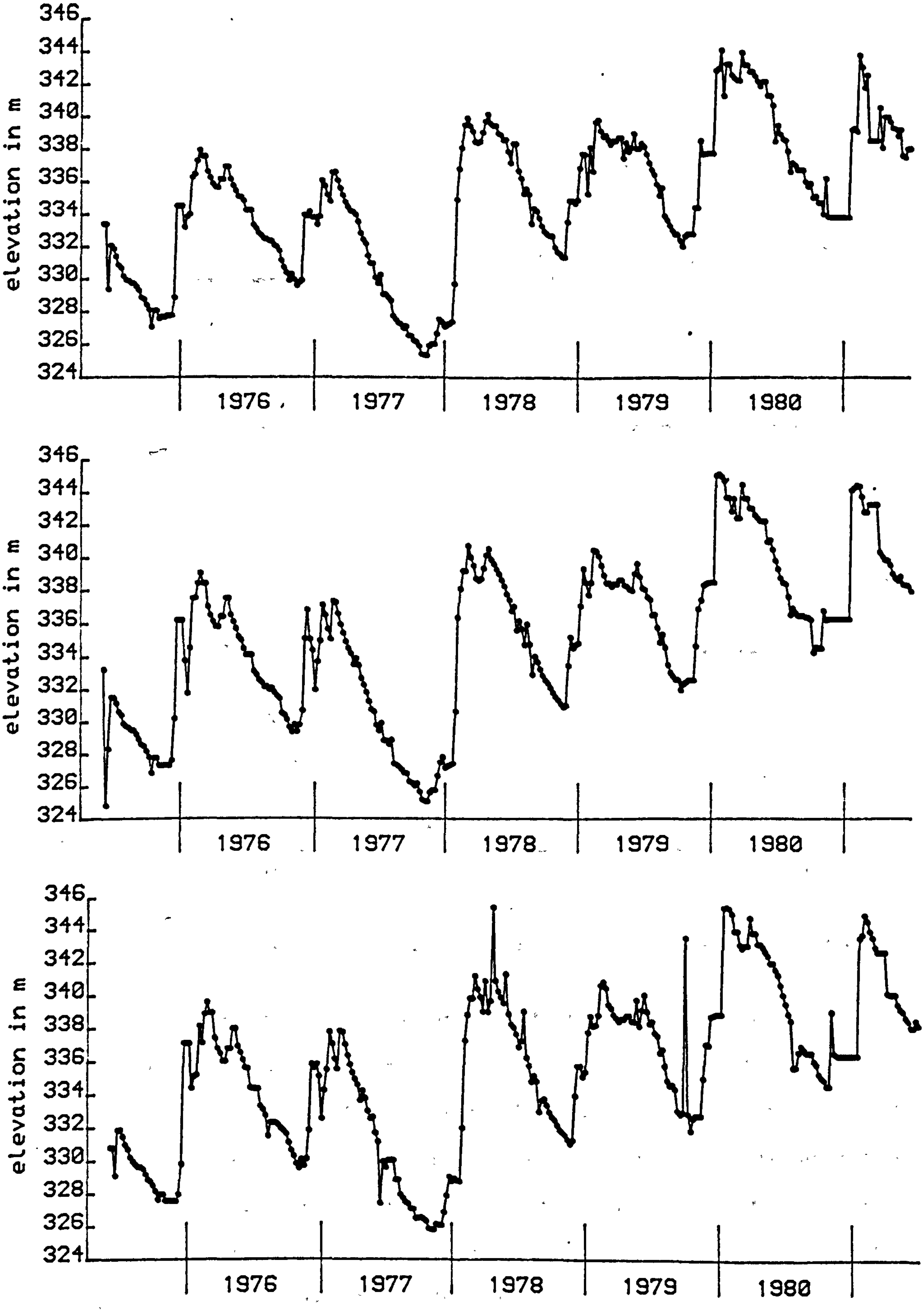
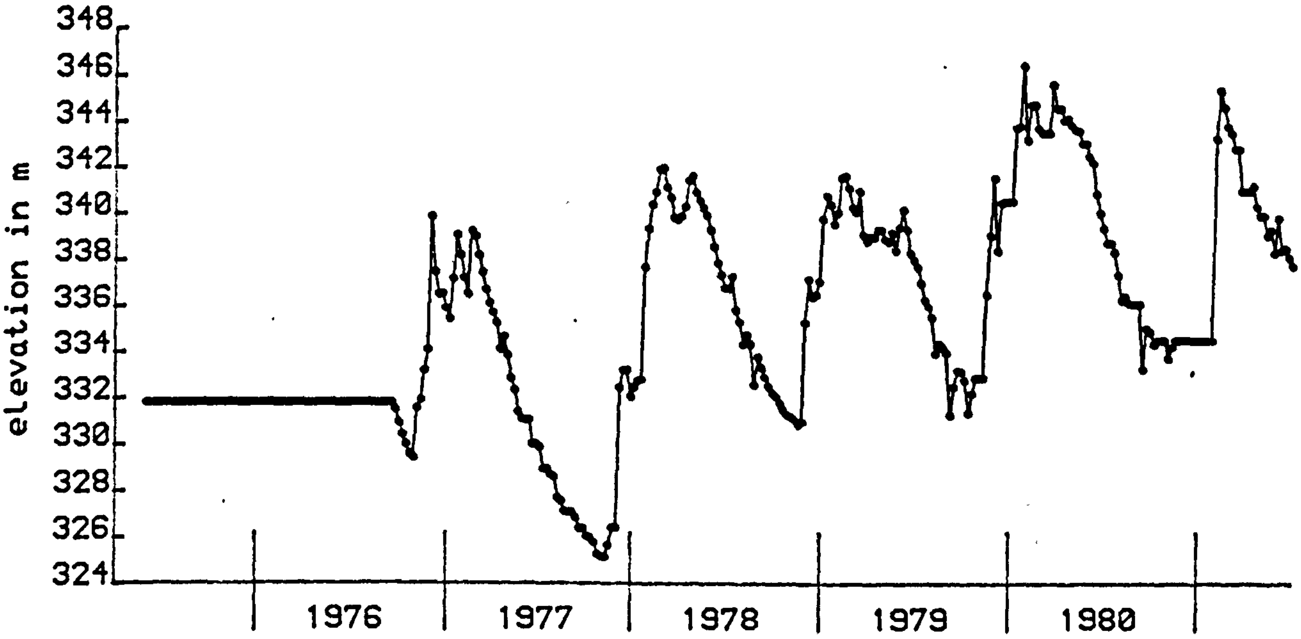


Fig 12.15 Hydrographs of the wells: a) P1, b) P7 and c) P8, sunk in aquifer 1.



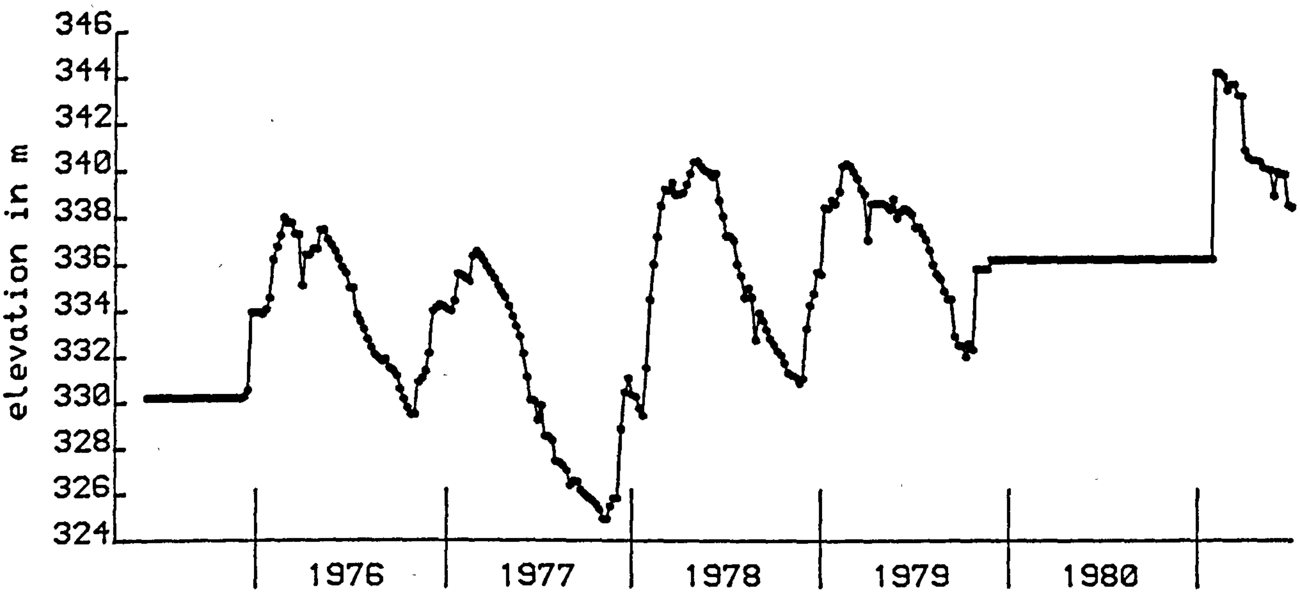


Fig 12.16 Hydrographs of the wells a) P11 and b) 320, sunk in aquifer 1.

The hydrographs of the wells of this group show a similar fluctuation pattern to that of the observation wells of group A of aquifer 1, the only difference being that the upper fluctuations of the groundwater level (ie at the end of the wet season) show values higher than those occurring in the wells of group A. The lower groundwater levels recorded in the wells of both groups A and B do, however, almost coincide. Furthermore, the hydrographs of the wells of group B show short-term fluctuations on the rising limbs, ie during the wet seasons - recharging periods of aquifer 1. The differences observed in upwards fluctuation of the groundwater level in the wells of these two groups ranged up to 10 m (Fig 12.17).

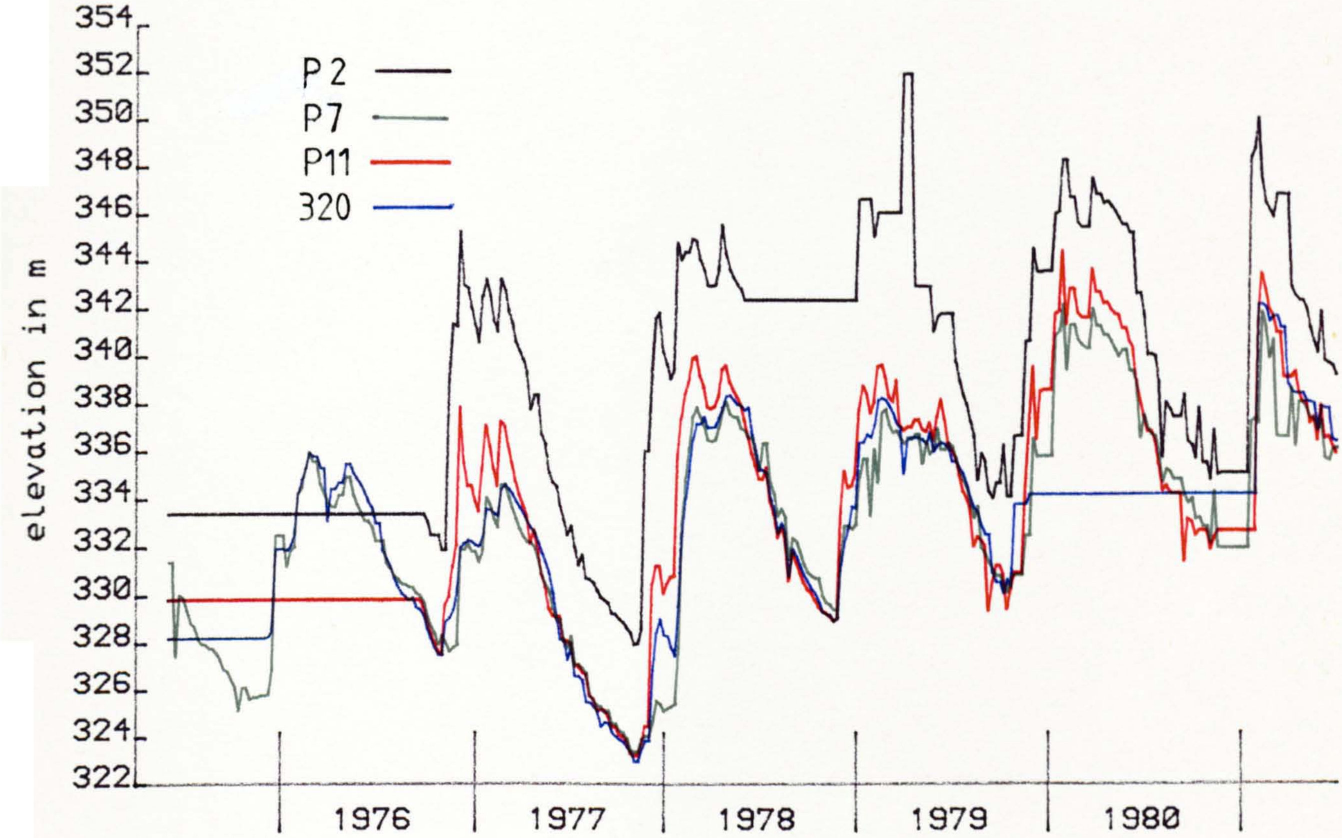


Fig 12.17 Hydrographs of the wells P1, P2, P11 and 320 (group B), sunk in aquifer 1.

The area in which the wells of group B are sunk is traversed by a tributary of the Alfios river, the Kyparissia stream, which flows mainly during winter and spring. For a short distance of less than 200 m, it flows over the limestone outcrop at an elevation of about 360 m and is thus in hydraulic continuity with aquifer 1. This stream is always influent to aquifer 1 during its entire period of flow from autumn to late spring, as can be seen from the form of the water table/piezometric surface in this area (Figs 12.23 to 12.34).

The amount of water percolating down to the aquifer from this stream depends on the discharge of the stream, the water table level in the aquifer, ie the existing hydraulic gradient and, predominantly, on the permeability of the stream bed and the limestone in the adjacent area.

Unfortunately, data for the stream discharge rate do not exist, but it can be assumed that the discharge of the stream is higher during years with heavy rainfall. If the short-term fluctuations in the groundwater level shown by the well hydrographs of this group are compared with the rainfall graph of the Karytena station (Fig 12.12) (bearing in mind that heavy rainfall provokes a corresponding rapid increase in the stream discharge rate, due to the increase in its direct run-off component) a good correlation is seen to exist between them. The same holds true when the total annual rainfall and the upwards fluctuation of the groundwater level recorded in these wells are compared.

Furthermore, it can be seen that both the long-term and short-term upward fluctuations of the groundwater level are greater in wells P2 and P11 (Figs 12.14 and 12.15a) which are situated closer to the stream. Due to their proximity to the stream (ie to the point of recharge of aquifer 1), these wells respond greatly to the increases in the induced percolation of water into aquifer 1, resulting from an increase in the discharge rate of the stream, ie following a period of heavy rainfall in winter storms.

Group C

The third category comprises the groundwater hydrographs of the nine production wells, F1 to F5, F8, F9, M1 and M2, sunk in aquifer 1 (see Fig 12.3 for their positions). Their hydrographs are presented in Figures 12.18 to 12.21.

In most of these well hydrographs, a rest water level and a pumping level can be recognised, corresponding to the periods when they were in operation. These two levels in the wells F3, F8 and, to a lesser extent, in wells F4 and F5 are, in fact, not distinct.

The rest water levels recorded in all these production wells coincide with the groundwater levels recorded in the observation wells of the first category and show identical long-term fluctuations. Short-term fluctuations in the rest water level do not occur here.

The pumping level, which is a function of the pumping of the well, differs markedly for each of these production wells. It depends on the discharge rate of the well, its distance from the recharge area and water boundaries and on local and seasonal factors such as heterogeneity of the aquifer, rest water level in the aquifer and discharge rate of the Alfios river by which they are fed (see Section 12.1.5.3).

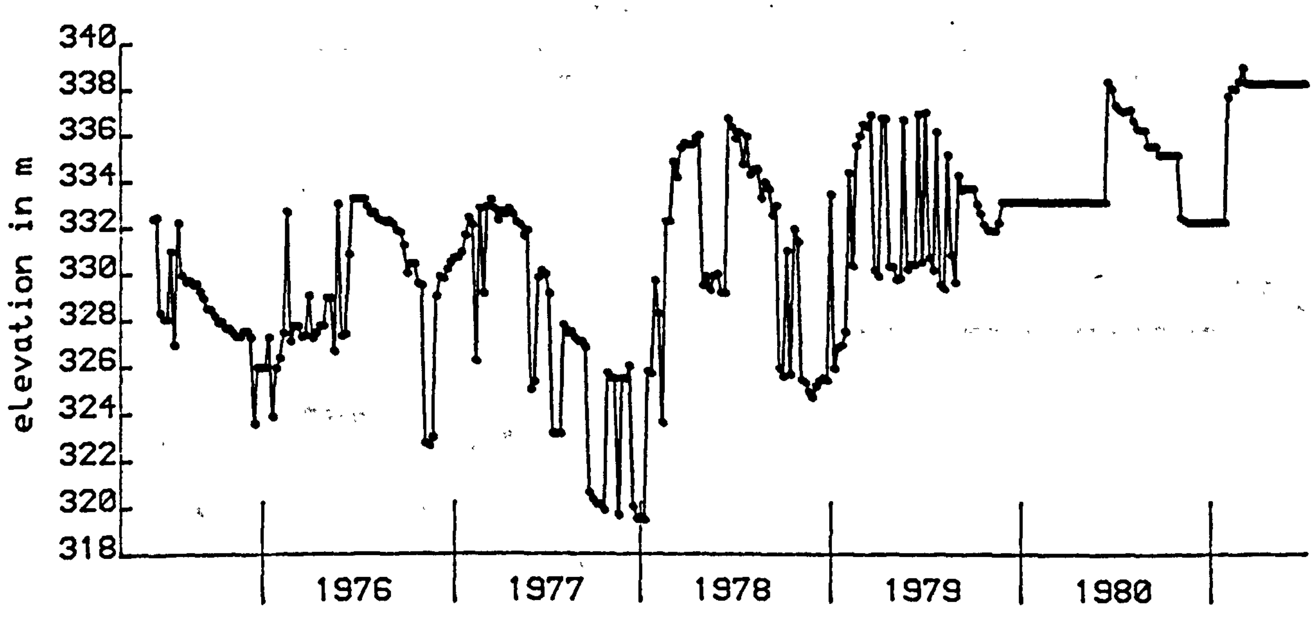


Fig 12.18 Hydrograph of the production well F1, sunk in aquifer 1.

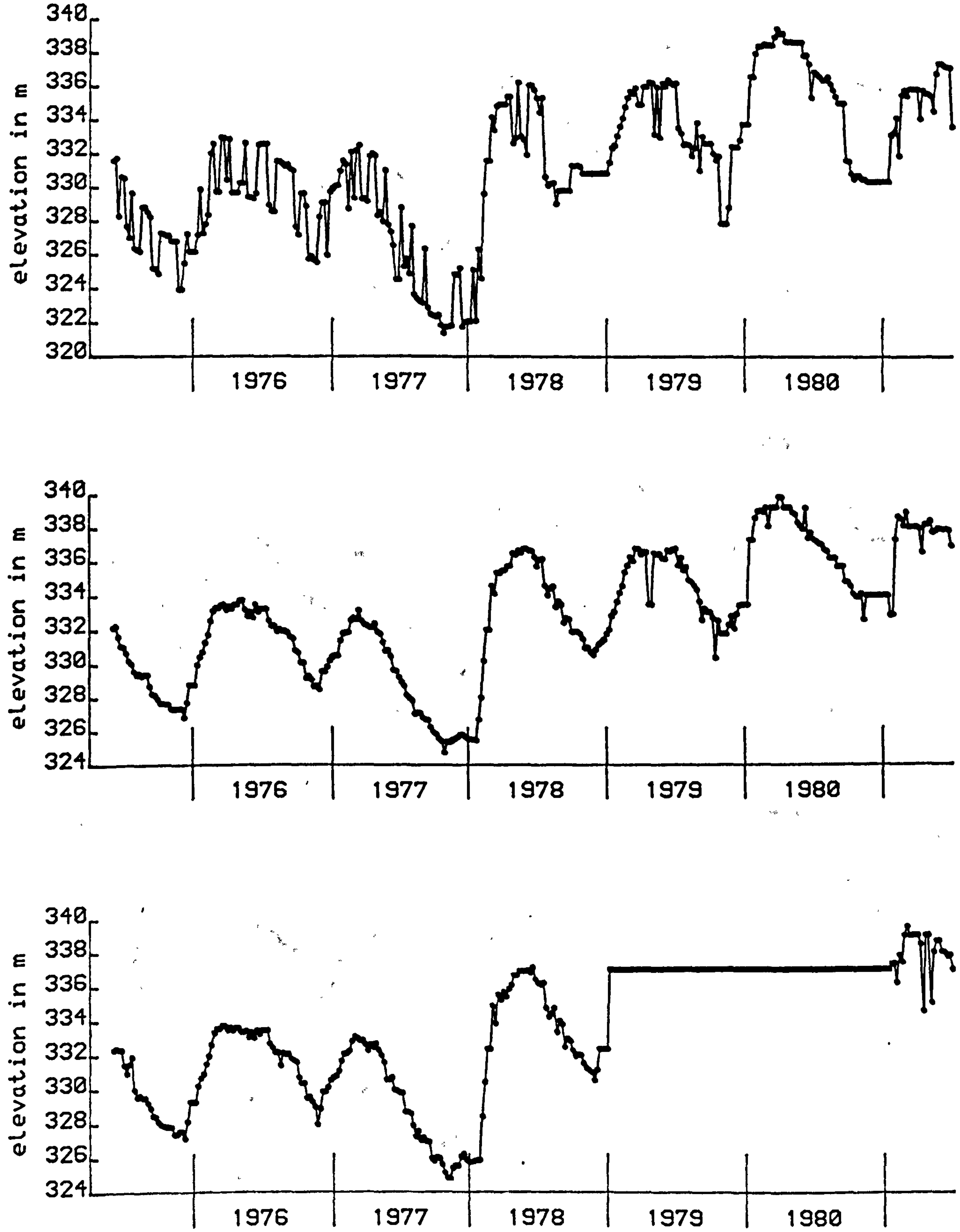


Fig 12.19 Hydrographs of the production wells: a) F2, b) F3 and c) F4, sunk in aquifer 1.

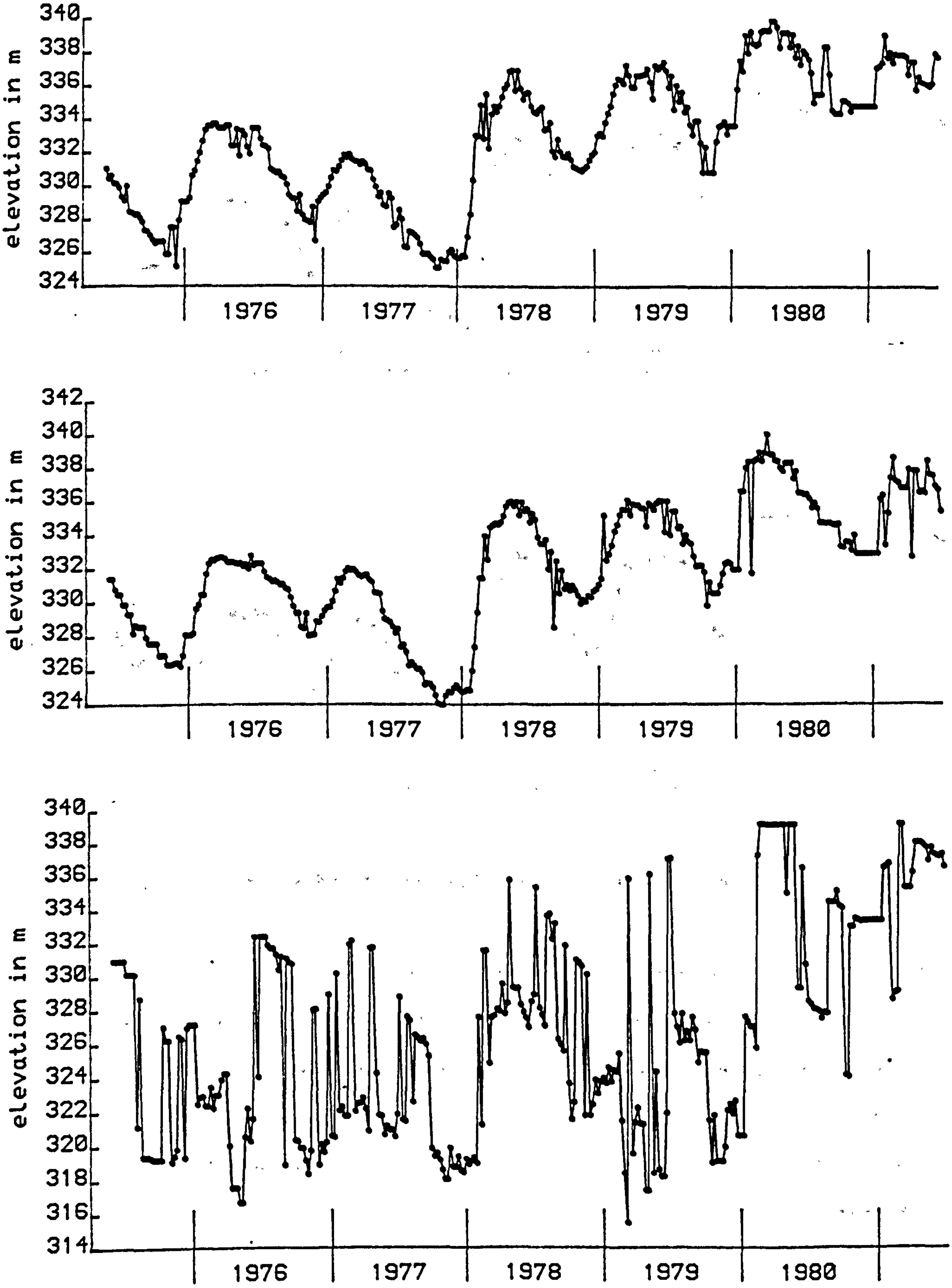


Fig 12.20 Hydrographs of the production wells: a) F5, b) F8 and c) F9, sunk in aquifer 1.

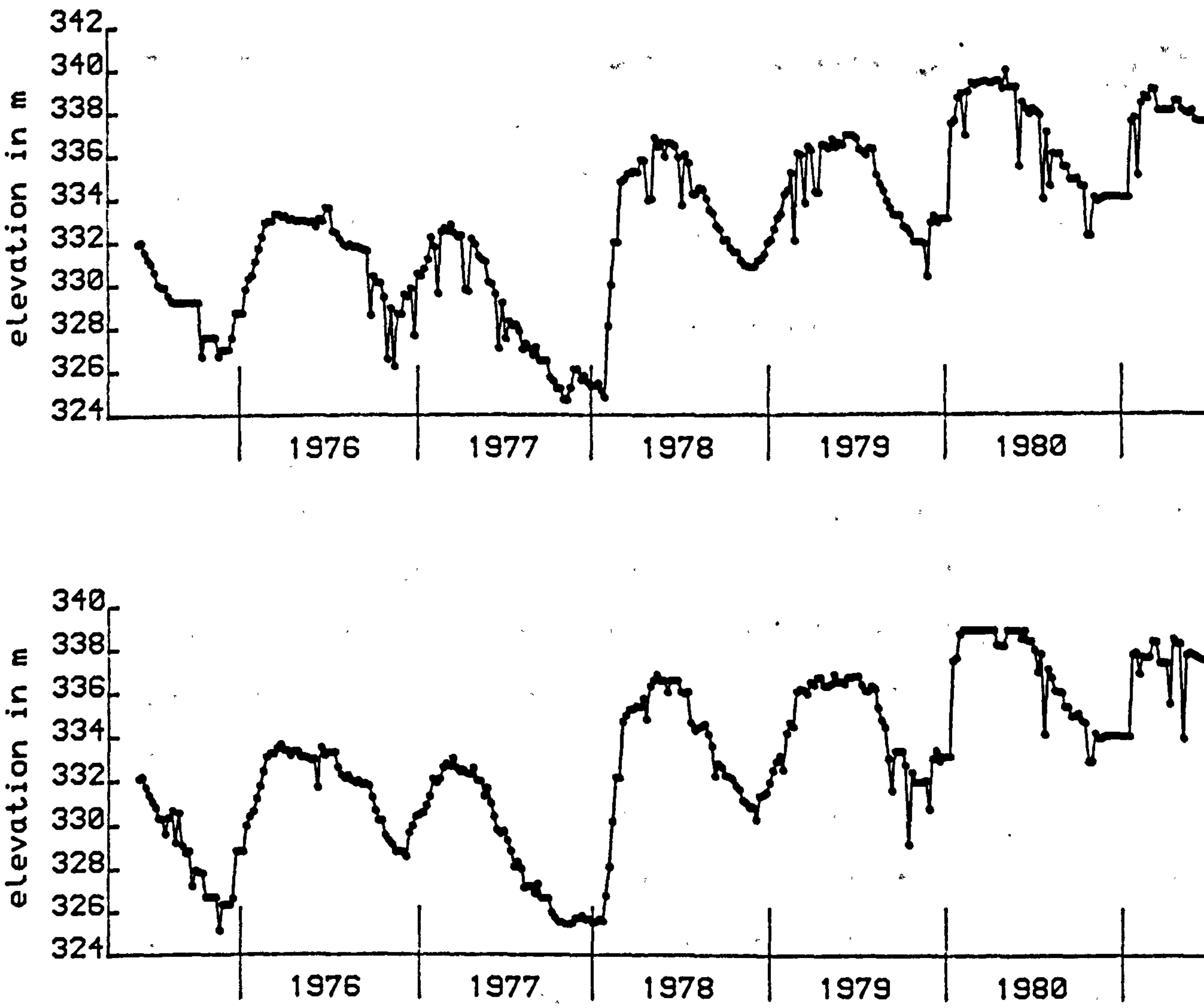


Fig 12.21 Hydrographs of the production wells: a) M1 and b) M2, sunk in aquifer 1.

Finally, well P9, situated in the northern part of aquifer 1, next to the Panagia spring (Fig 11.8), exhibits an almost flat hydrograph (Fig 12.22). The water table recorded in this well lies at an elevation between 331 and 332 m, which is slightly higher than or the same as the elevation of the issuing point of the Panagia spring at 331.2 m. Only during the dry season of 1977, when the lowest groundwater level recorded in aquifer 1 occurred, did the water table in well P9 fall below this elevation and hence follow the fluctuation of the groundwater level in aquifer 1. This is clear evidence that the Panagia spring and also the other springs situated around this area (eg Opiste Panagia spring) are hydrogeologically associated with aquifer 1.

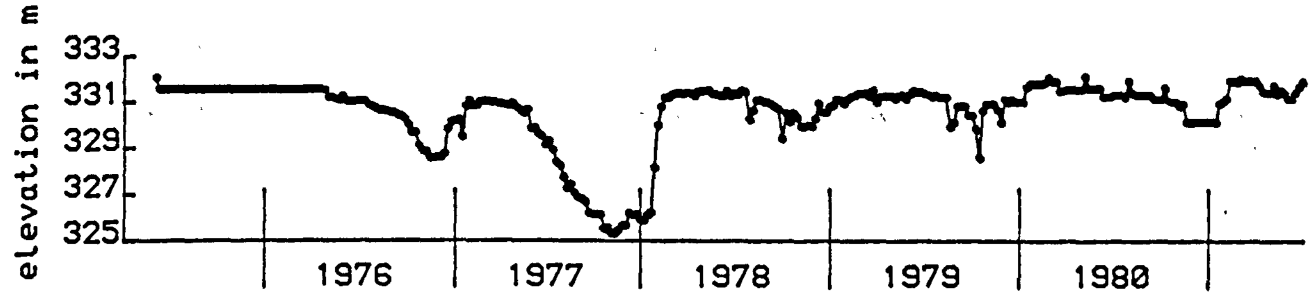


Fig 12.23 Hydrograph of the well P9, sunk in aquifer 1.

12.1.4.2 <u>Piezometric maps</u>

Groundwater contour maps, or piezometric maps, which, due to the fact that aquifer 1 is confined along most of its extent, correspond to the higher and lower groundwater levels recorded for each year (Appendix III), were drawn for the period of observation (1975-1981) (Figs 12.23 to 12.34).

The piezometric maps were drawn to a scale of 1:8,000, the observation and production wells being indicated on the same maps. The hydraulic head (in m) (ie the height equal to the elevation of the top of the well, minus the depth to the piezometric surface/water table) at each well was plotted and contour lines of equal hydraulic head (isopiezometric lines) were then drawn.

The dates selected for the maps to be drawn (ie at which the lower and higher groundwater levels occurred), were based on the study of the well hydrographs.

The time of year at which the higher groundwater level occurred is quite specific and is around the middle of May. On the contrary, the time of year at which the lower groundwater level occurred shows a degree of variation. It occurs mainly during the second half of November but sometimes just a little earlier and, in one case, in early December (Table 12.3). This is to be expected, since the time at which the lower groundwater level is reached and also its absolute value depend on the time and quantity of the early autumn rainfalls.

Study of the piezometric maps reveals that the distribution of the hydraulic head in the aquifer, for most of its extent, is quite flat with only small differences, ranging from a few centimetres to just under 1 m, in the levels being recorded in adjacent wells. On the south-western side of aquifer 1, in the area east of the village of Kyparissia, a steeper hydraulic gradient is recognised, resulting from the Kyparissia stream, a minor tributary of the Alfios river, being influent to aquifer 1 during its entire period of flow.

The mean elevation of the higher and lower piezometric surfaces for each year (ie representing the flat area of aquifer 1), together with the respective dates on which they occurred, are given in Table 12.3.

As will be discussed in more detail later in this chapter, the production wells F3, F8, F4 and F5, sunk in aquifer 1 and situated around the Kyparissia bridge, show only a minor drawdown when pumped. Furthermore, the wells F1 and F2, situated a little further from the

Year	Higher piezometric surface		Lower piezometric surface	
	Date of occurrence	Elevation in m above sea-level	Date of occurrence	Elevation in m above sea-level
1975	-	-	7/12	327-328
1976	16/5	333-334	21/11	329-330
1977	15/5	331-332	13/11	325-326
1978	14/5	336-337	12/11	331-332
1979	13/5	336-337	18/11	332-333
1980	11/5	339-340	16/11	334-335
1981	17/5	338-339	-	-

Table 12.13 Higher and lower piezometric surface recorded in aquifer 1.

bridge, show a relatively greater drawdown and do not form an extensive cone of depression as might be expected. This striking feature of aquifer 1 is due to the high permeability of the aquifer and to the fact that these wells are fed directly from the Alfios river through individual channels in the area south of and around the Kyparissia bridge (see Section 12.1.5.3 for details).

This phenomenon was also observed when constructing the piezometric maps. Characteristic is the example of well F1, which when being pumped had, on average, a level 6.0 m below the rest water level (see well hydrograph, Fig 12.18). In contrast, at the observation well 311, situated just 5 m away from the production well F1, the drawdown in relation to well F1 averaged only 0.5 m (Fig 12.4a). Thus, in general, a cone of depression was not drawn around the production wells, even for those wells at which a relatively large drawdown was measured, due to the fact that the extent and the shape of the cone of depression resulting from their pumping were not accurately known.

Only around the well F9, at which a significant drawdown of 10-12 m was always recorded, was a cone of depression drawn. Even here, the extent and shape of the cone of depression cannot be well determined.

From the study of the piezometric maps (Figs 12.23 to 12.34), it can be seen that the Kyparissia stream which flows 400 m south of the village of Kyparissia in a W-E direction is always, throughout its entire period of flow, influent to aquifer 1, as the hydraulic gradient is always towards the aquifer. The recharge area, along which the stream flows over the limestone and through which the stream water percolates down to the aquifer, is limited to a distance of less than 200 m. This area lies at an elevation of approximately 360 m.

No constant hydraulic gradient from the recharge area to the aquifer can be recognised. Furthermore, there is no correlation between the hydraulic gradient and the level of the water table/piezometric surface.

The factors which determine the hydraulic gradient and hence the amount of water percolating downwards to the aquifer (assuming that the limestones have a constant permeability (k value) and that no changes occur in the nature and therefore in the degree of permeability of the bed of the stream, eg changes resulting from a block-up (sealing) of the channels through which the water percolates downwards) can be summarised as follows:

Firstly, by definition, the gradient is determined from the existing difference between the elevation of the recharge area of the stream (ie the elevation at which the stream water percolates downwards to the aquifer) and that of the water table of the aquifer. The lower the water table in the aquifer, the steeper the gradient.

Secondly, the amount of water percolating downwards to the aquifer and hence the hydraulic gradient, when there is a constant k-value of the adjacent limestone and of the stream bed, depends on the discharge rate of the stream. The greater the discharge in the stream, the more water is available for percolation, for higher pressure conditions exist on the stream bed when there is an increased discharge rate of the stream.

Unfortunately, data on the stream discharge rate are not available. This stream drains a catchment of a relatively small size (approximately 4.2 km^2). The run-off of the stream originates from direct run-off, as its base-flow component is very low. Due to the small size of its catchment, only a short time elapses between a period of heavy rainfall and the corresponding increase in the stream's discharge rate. The comparison between the rainfall graph (Fig 12.12) and the hydrographs of the wells situated around this area of discharge of aquifer 1 shows that a high degree of correspondence exists between the upwards fluctuation of the water table of aquifer 1 in this area and the amount of water precipitated at particular times of the year.

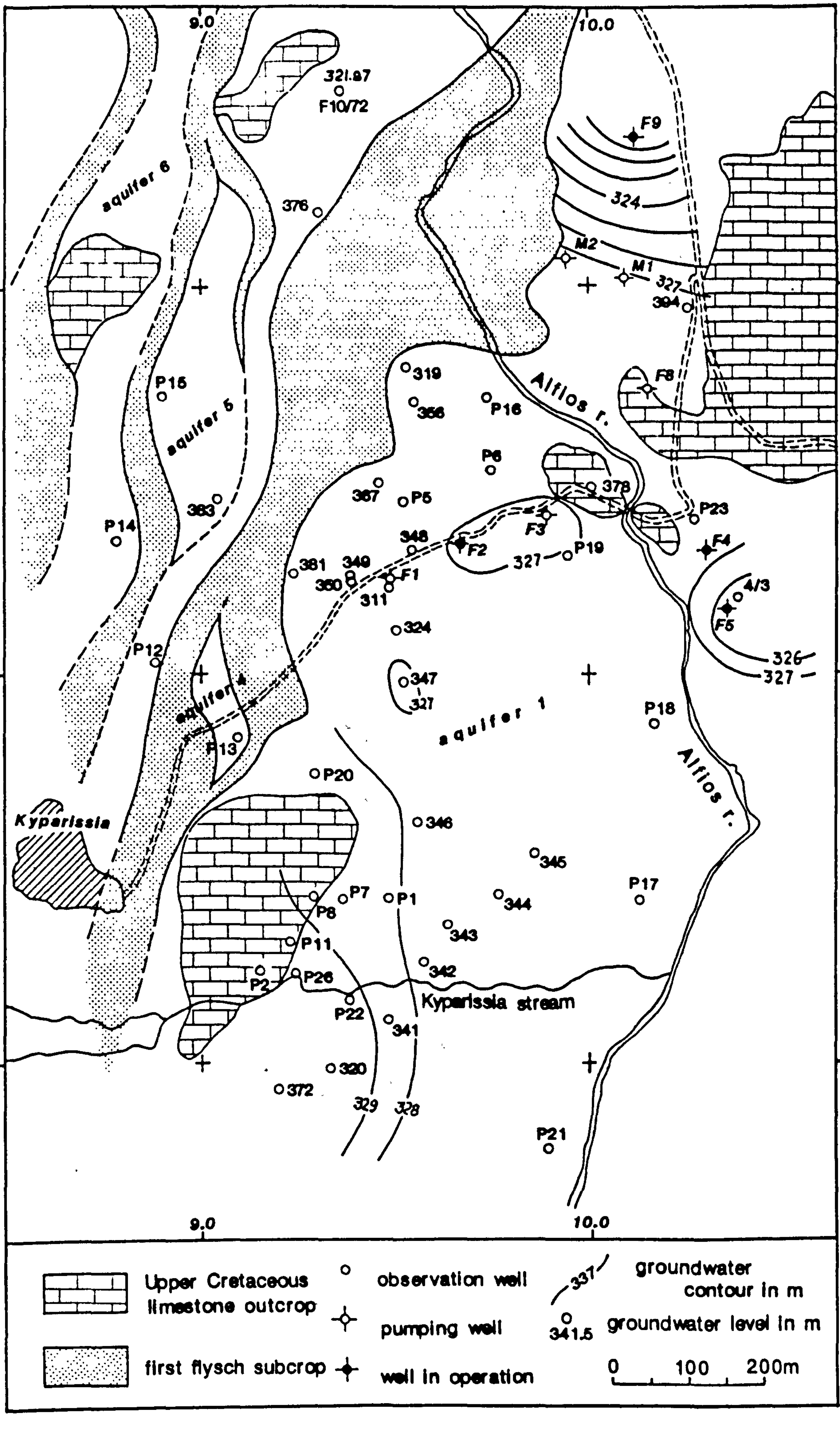


Fig 12.23 Map of the hydraulic head distribution in aquifer 1; lower groundwater levels recorded on 7 December 1975.

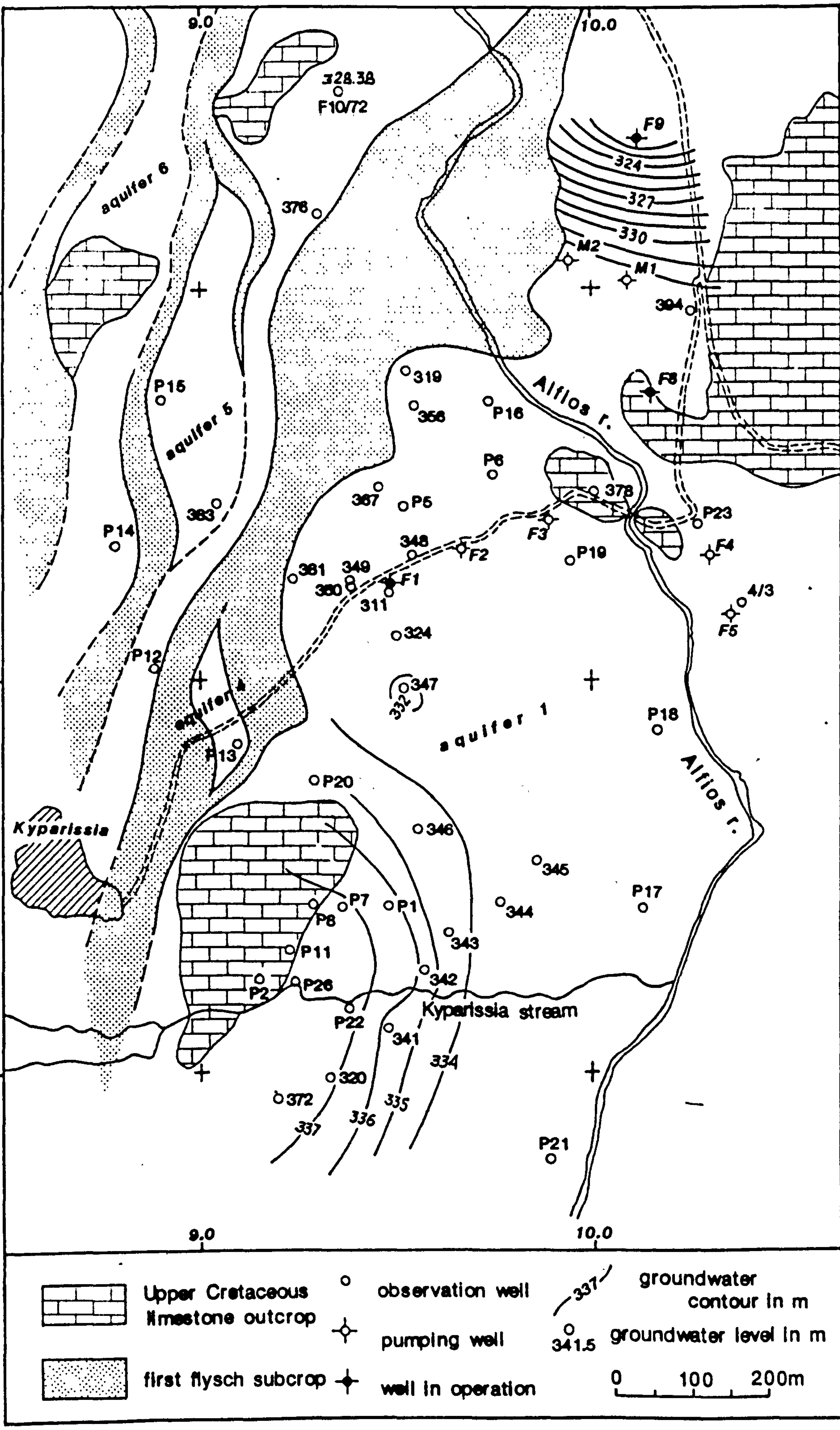


Fig 12.24 Map of the hydraulic head distribution in aquifer 1; higher groundwater levels recorded on 16 May 1976.

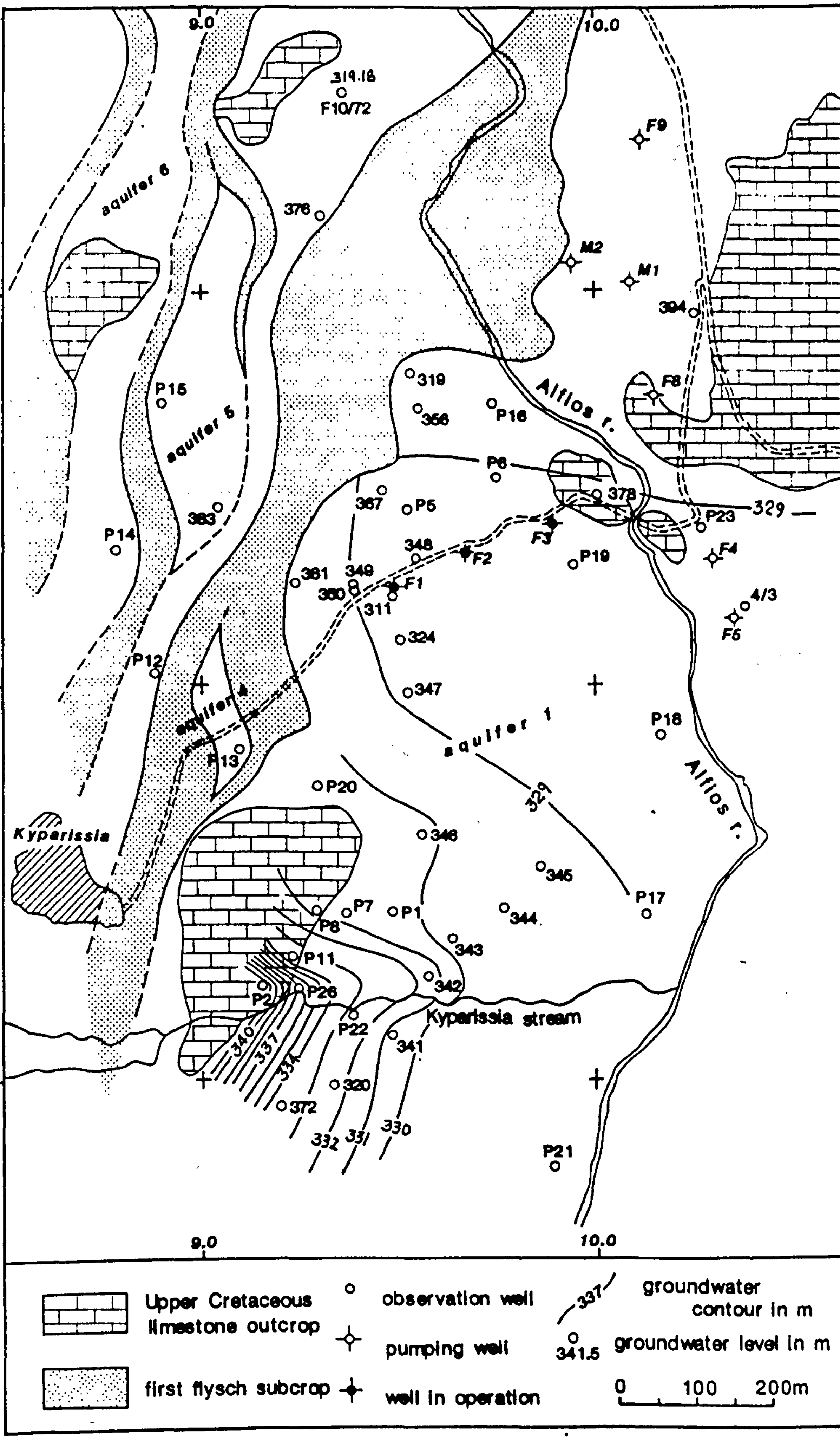


Fig 12.25 Map of the hydraulic head distribution in aquifer 1; lower groundwater levels recorded on 21 November 1976.

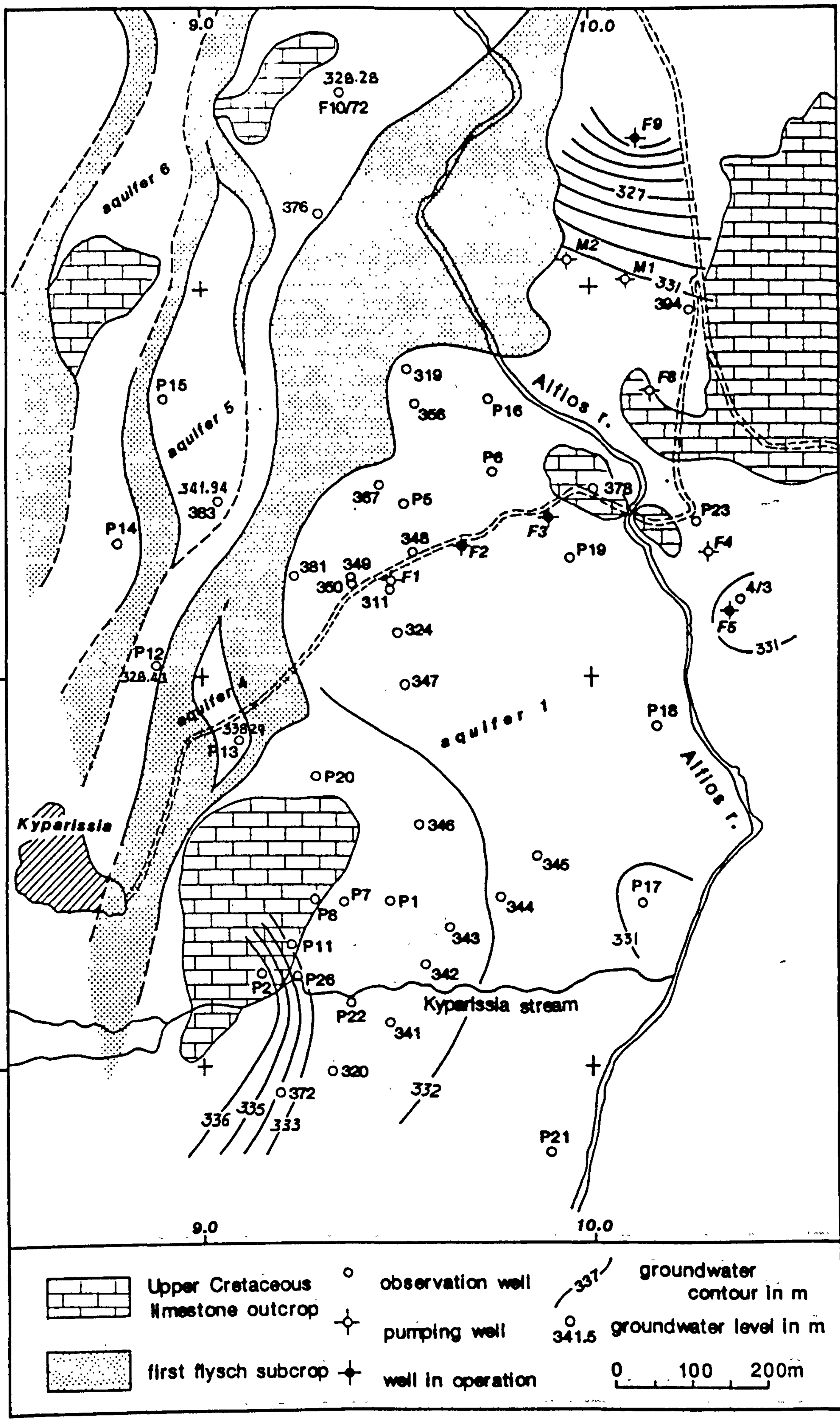


Fig 12.26 Map of the hydraulic head distribution in aquifer 1; higher groundwater levels recorded on 15 May 1977.

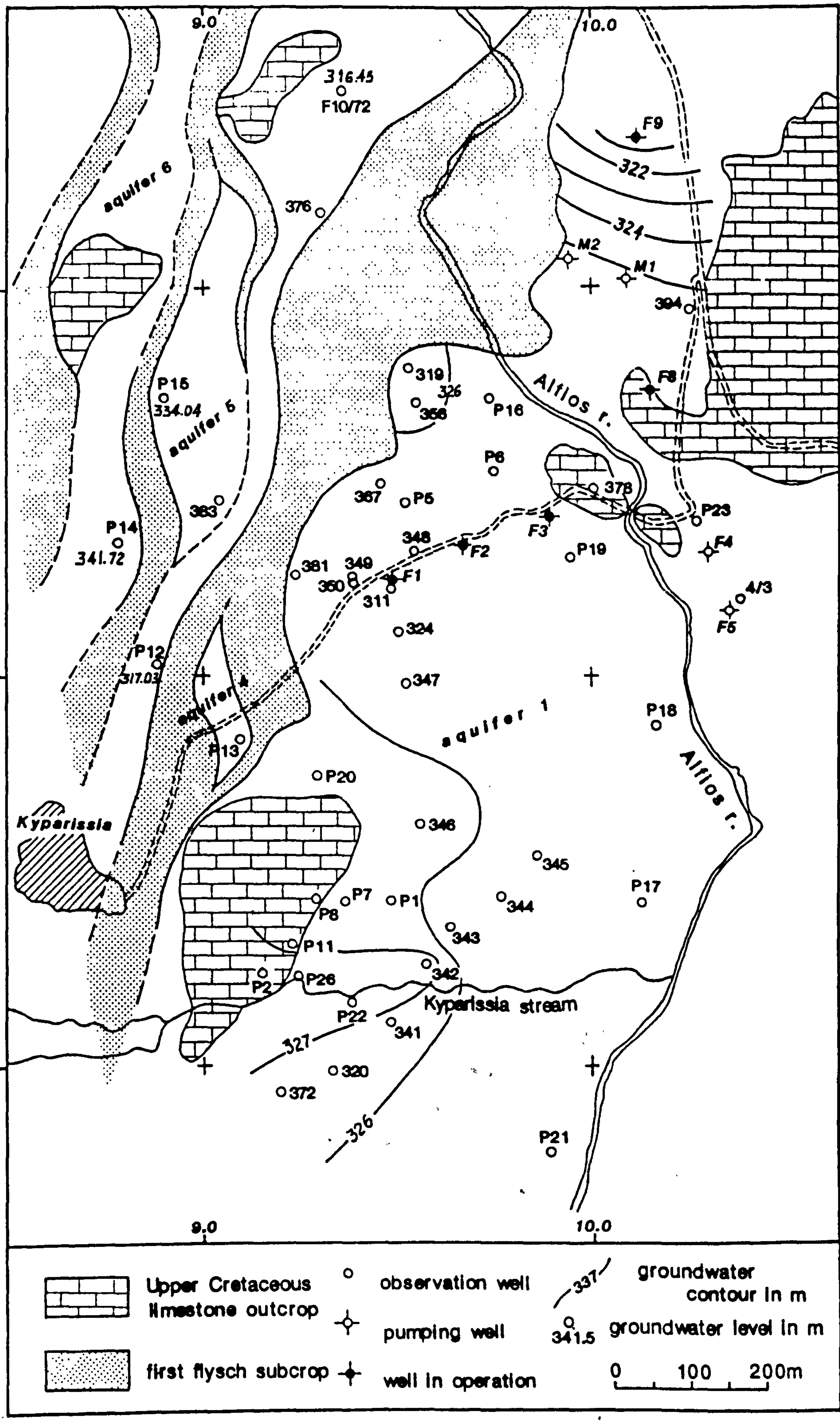


Fig 12.27 Map of the hydraulic head distribution in aquifer 1; lower groundwater levels recorded on 13 November 1977.

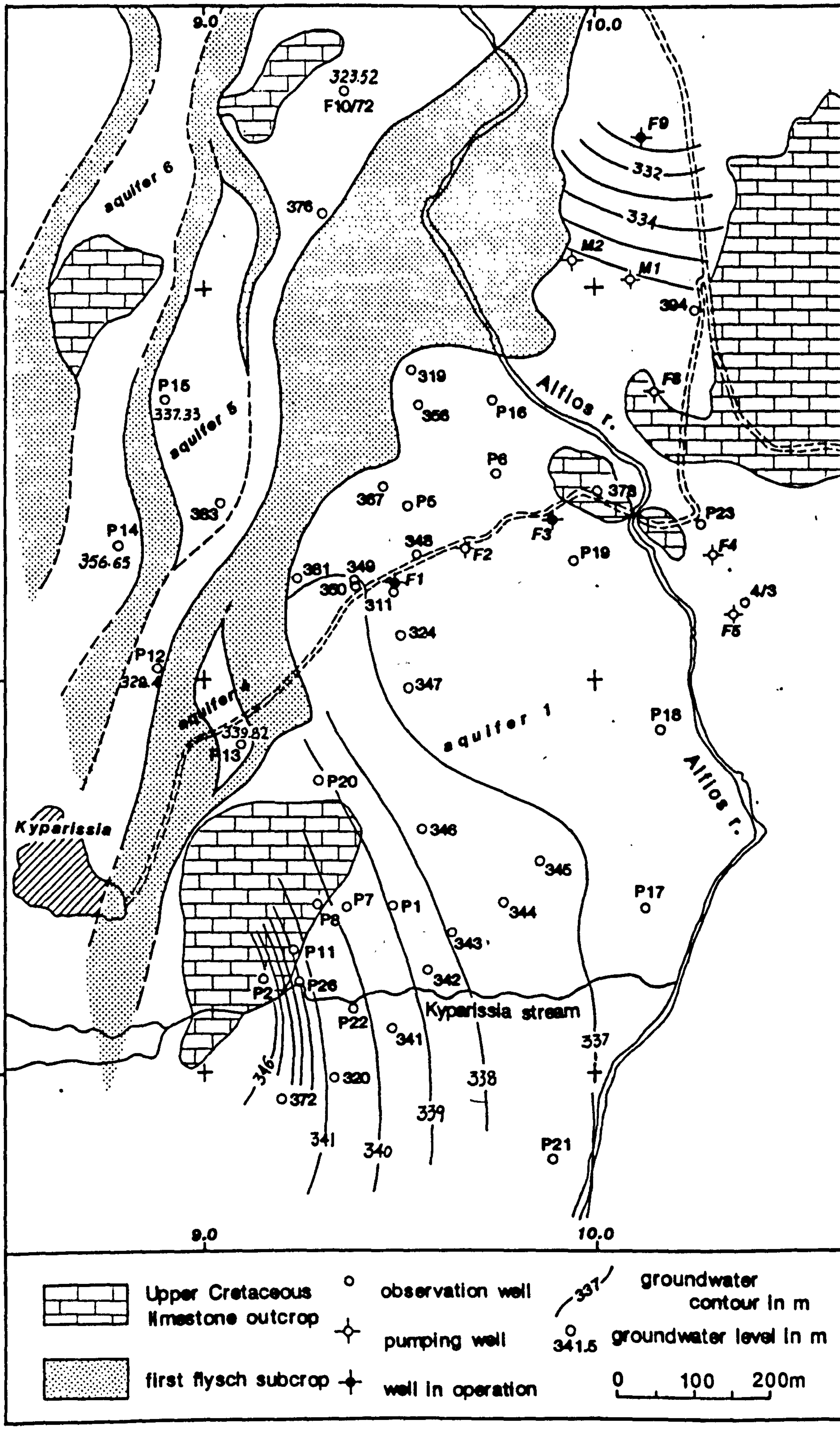


Fig 12.28 Map of the hydraulic head distribution in aquifer 1; higher groundwater levels recorded on 14 May 1978.

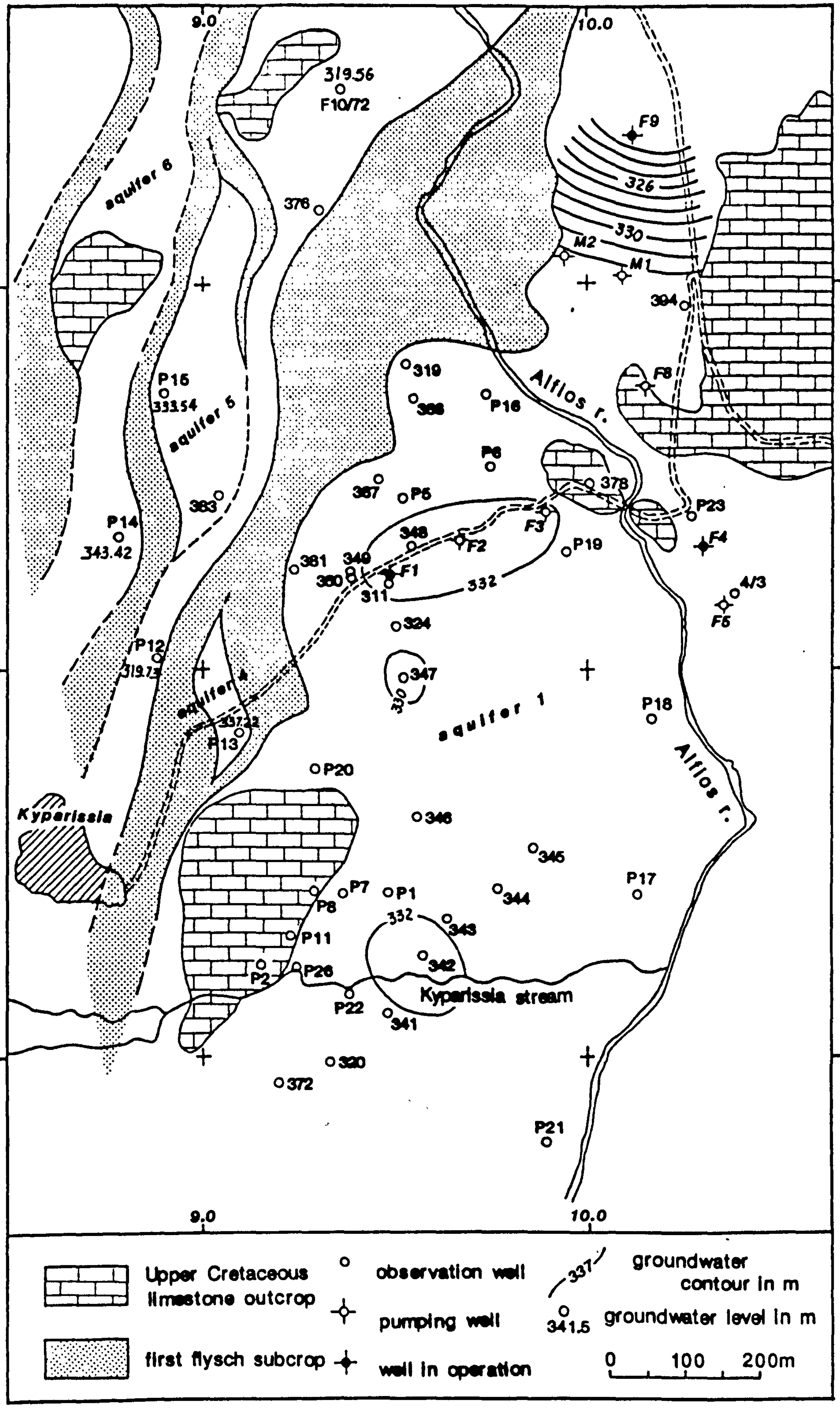


Fig 12.29 Map of the hydraulic head distribution in aquifer 1; lower groundwater levels recorded on 12 November 1978.

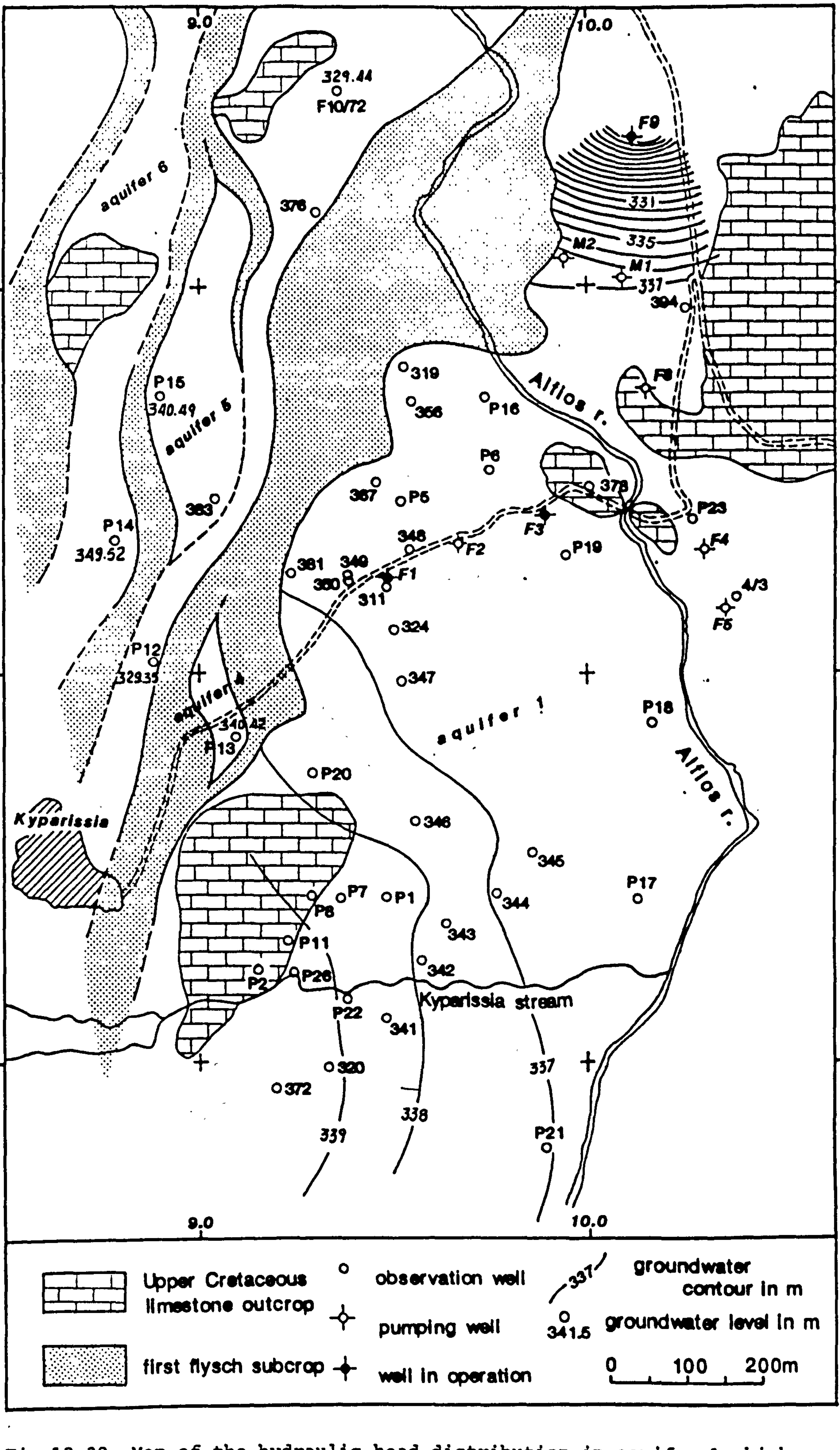


Fig 12.30 Map of the hydraulic head distribution in aquifer 1; higher groundwater levels recorded on 13 May 1979.

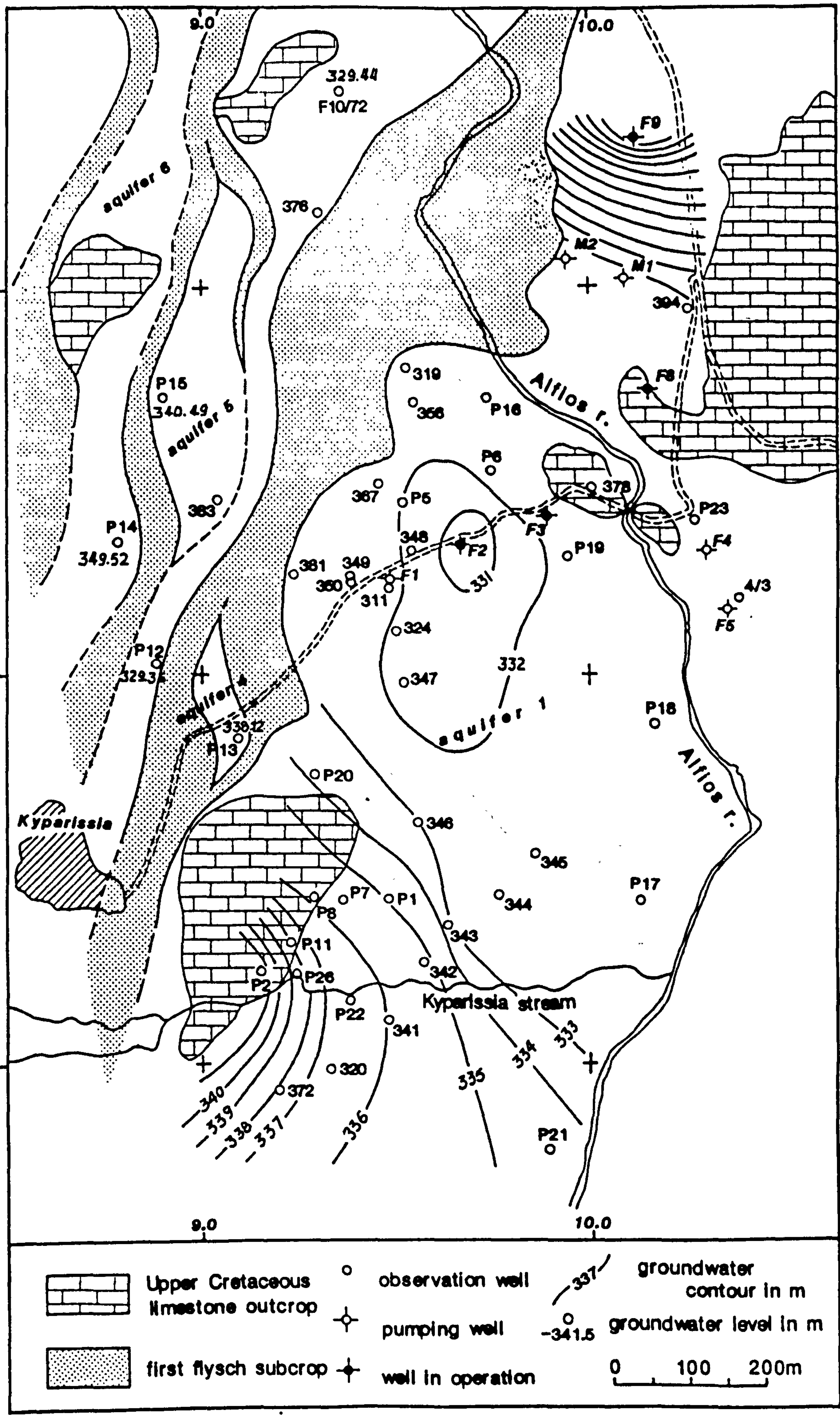


Fig 12.31 Map of the hydraulic head distribution in aquifer 1; lower groundwater levels recorded on 18 November 1979. .

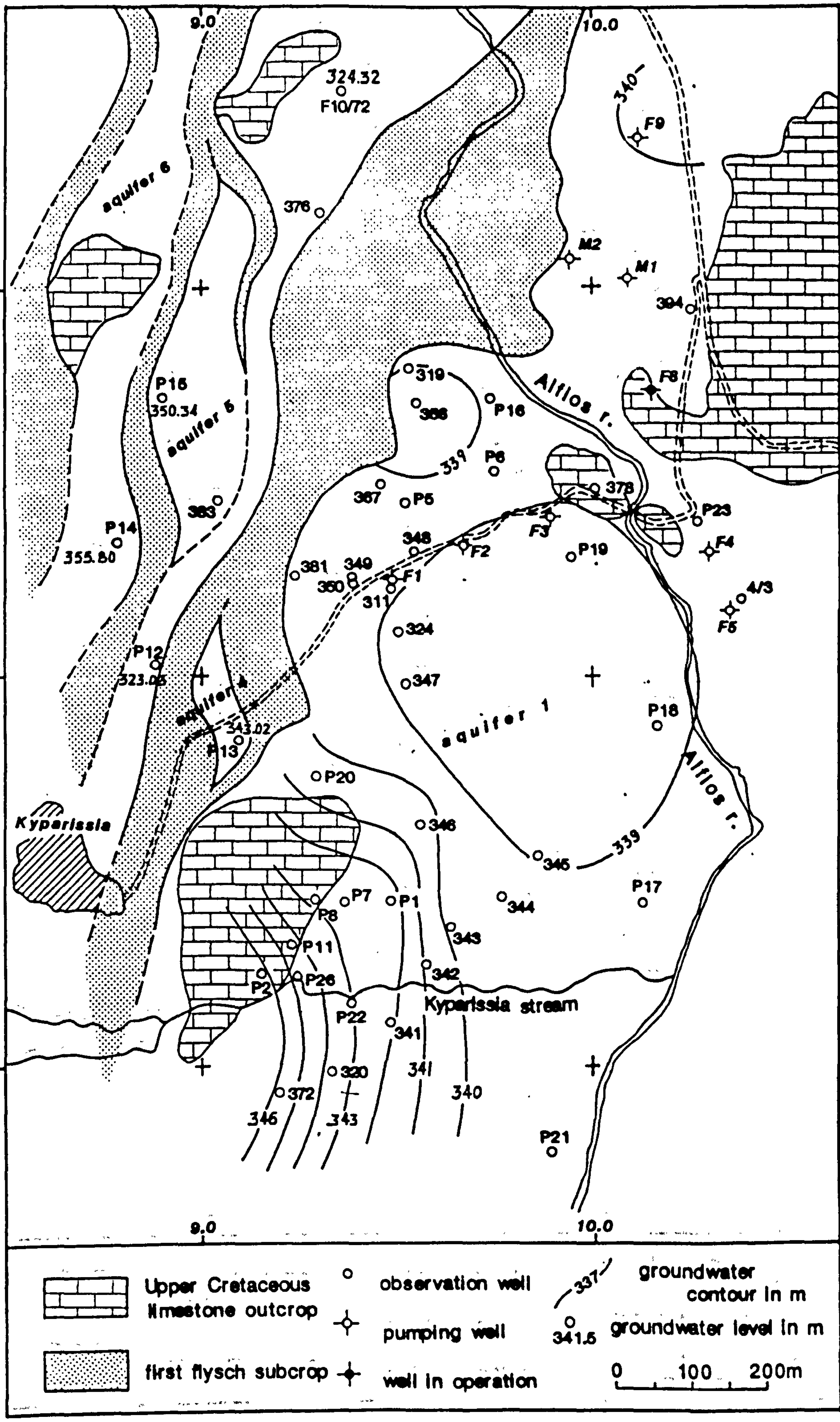


Fig 12.32 Map of the hydraulic head distribution in aquifer 1; higher groundwater levels recorded on 11 May 1980.

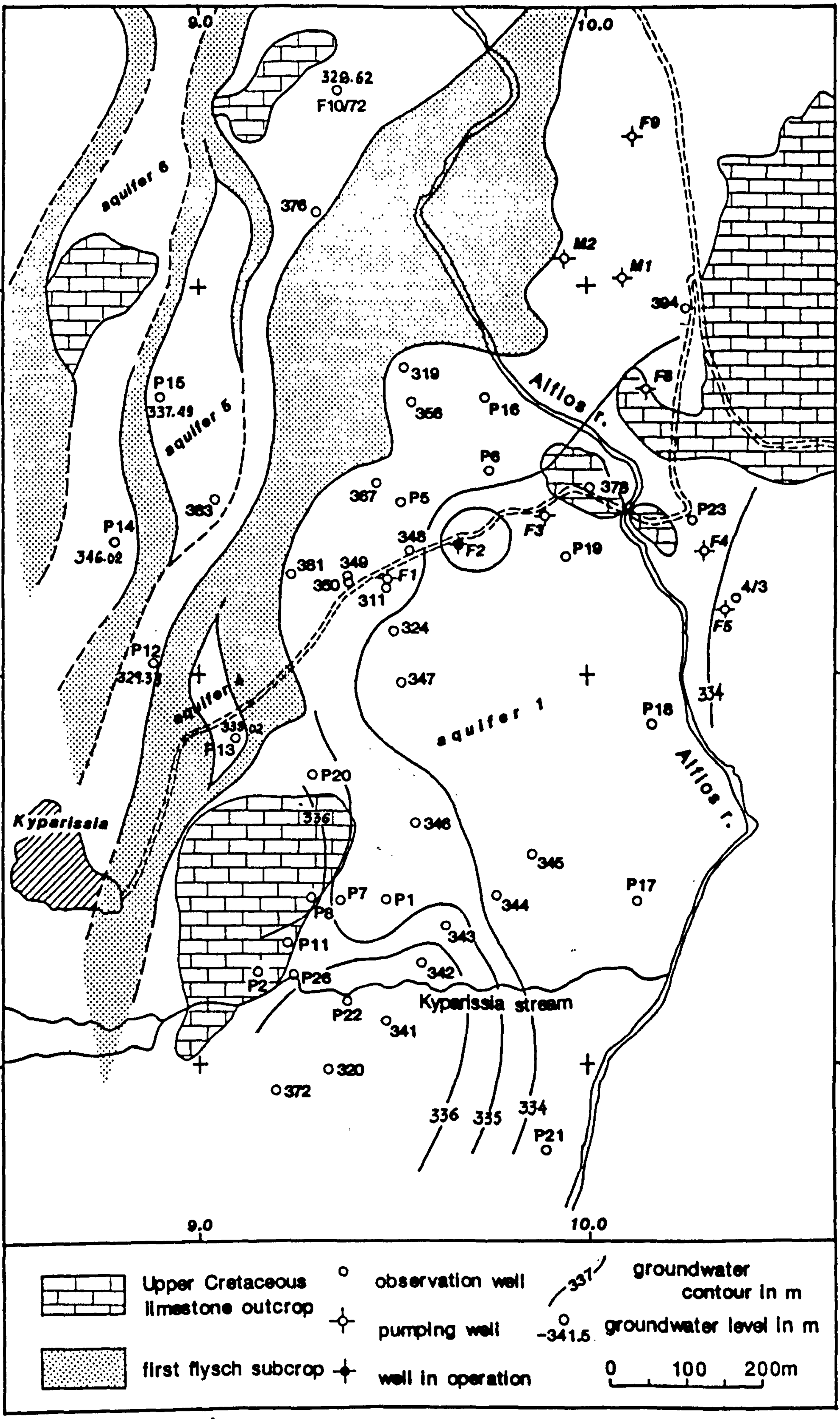


Fig 12.33 Map of the hydraulic head distribution in aquifer 1; lower groundwater levels recorded on 16 November 1980.

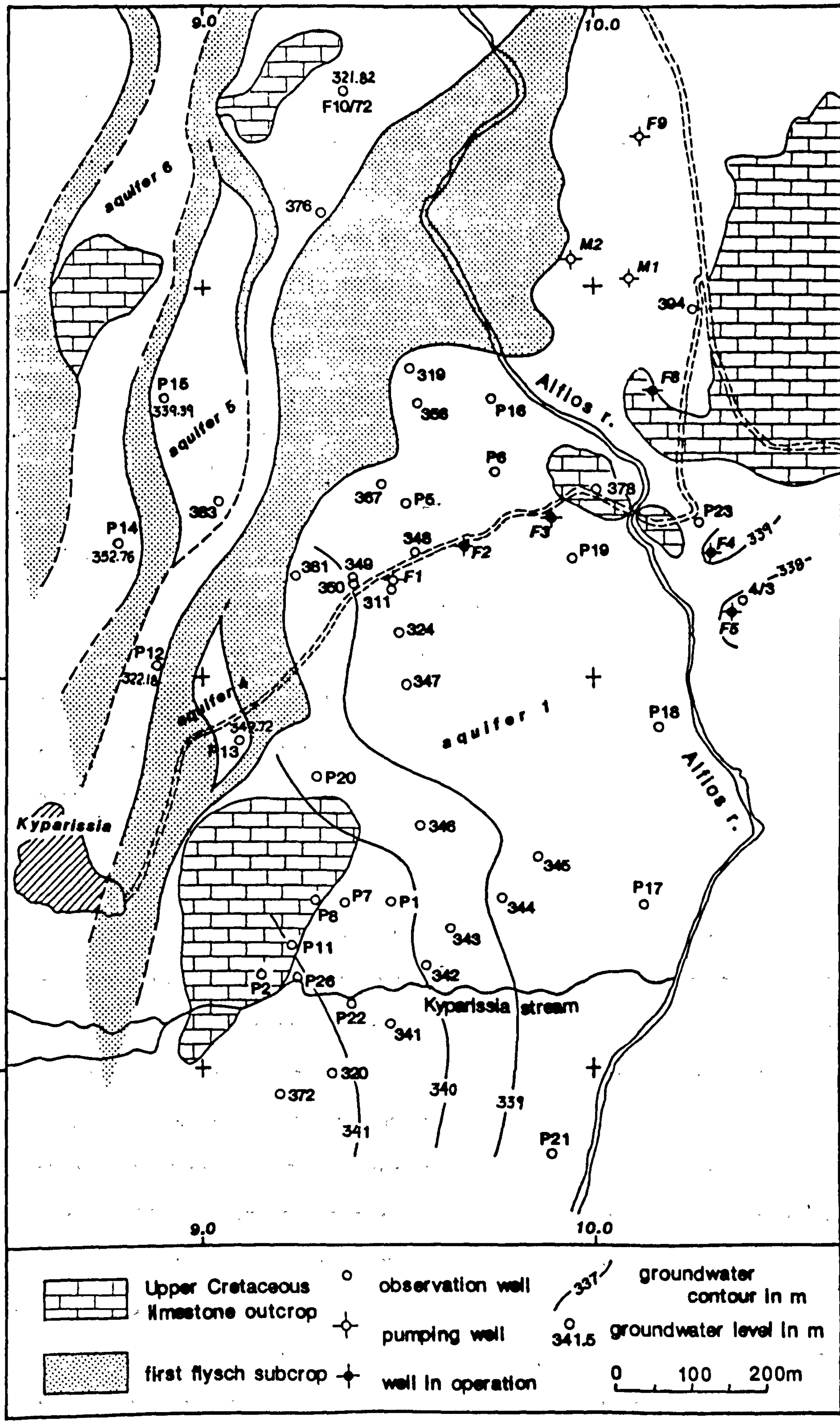


Fig 12.34 Map of the hydraulic head distribution in aquifer 1; higher groundwater levels recorded on 17 May 1981.

Study of the piezometric maps does not reveal a hydraulic relationship between the Alfios and aquifer 1, ie it does not establish the influent or effluent character of the Alfios.

This is due to the large area of hydraulic continuity between the Alfios and the underlying aquifers which causes them to be a single hydrogeological unit.

12.1.5 Pumping tests

12.1.5.1 Introduction

Pumping tests can yield much information regarding the hydraulic parameters of an aquifer as well as of the borehole itself.

The most important parameters that can be derived describing the aquifer as a fully developed source of water are transmissivity and hydraulic conductivity (both of which are directly related to permeability) and storage coefficient, for a confined aquifer, or specific yield, for an unconfined aquifer (related to compressibility and porosity respectively).

Various equations and types of curves from which the various parameters can be obtained have been formulated for the analysis of the pumping tests, in order to demonstrate the relationships existing between discharge and transmissivity-storativity of the aquifer. A few are briefly outlined in the next Section. These mathematical methods can be applied if certain assumptions are made and conditions satisfied, although in nature it is not usually possible to find an ideal situation in which all the conditions are met. Some of these formulae have been developed specifically for various types of aquifer conditions, eg confined, unconfined, leaky.

The non-equilibrium formulae are now generally accepted as the most satisfactory, especially when the period of the pumping test is so prolonged that it far exceeds the time taken for the water to recover its original level after pumping has stopped.

These formulae have been developed on the basis of laminar flow in granular aquifers and their application in the karstic aquifers which, as is widely recognised, are dominated by fissure flow may not be entirely valid.

Due to the heterogeneous characteristics of karstic aquifers and to the mixture of linear and turbulent flow which can occur in such karstic aquifers, the extension of the aquifer coefficients (parameters) determined in a few boreholes to the whole area of the aquifer can only be made with certain reservations as to its accuracy and validity.

Finally, the accuracy of the results obtained from a pumping test increases when additional measurements are taken from several observation wells and so depends widely on how well the pumping test is organised and carried out.

12.1.5.2 Methods of pumping test analyses

A. Steady radial flow to a well

a) Thiem method

Thiem (1906) derived an equation, known as an 'equilibrium', which enables the hydraulic conductivity (K) or transmissivity (T) of a confined aquifer to be determined by means of data from a pumped well:

$$Q = 2\pi Kb \frac{h-h_w}{\ln(r/r_w)} \qquad (12.1)$$

where h_w = head at well face in m

h = head at distance r

r = distance of observation well from pumped well in m

r_w = radius of the pumping well in m

This equation can only be applied in the case of steady radial flow to a well and, furthermore, several conditions must also be met, as follows:

1. The aquifer should be of infinite areal extent.
2. The aquifer should be homogeneous, isotropic and of uniform thickness over the area being pumped.
3. Prior to the pumping, the piezometric surface must be horizontal or nearly horizontal.
4. The pumped well should penetrate the entire thickness of the aquifer and the flow to the well should be horizontal.
5. Discharge must be constant. The pumping test must continue at a uniform rate for sufficient time to approach a steady-state condition (ie one in which drawdown changes negligibly with time).

B. <u>Non-steady radial flow to a well</u>

a) <u>Theis' equation</u>

Theis (1935) was the first to formulate the equation existing between the drawdown measured in a nearby observation well and the rate of pumping, during the non-equilibrium state of pumping, ie he was the first to introduce the time-factor to the mathematics of groundwater hydraulics. He based his theory on the consideration that the hydraulics of an aquifer are analogous to an equivalent thermal system.

Theis' equation has the form:

$$s = \frac{Q}{4\pi T} W(u) \qquad (12.2)$$

where s = drawdown in m

T = transmissivity of the aquifer in m^2/day

Q = discharge rate in m^3/day, and

$$W(u) = \int \frac{e^{-u}}{u} du \quad \text{- called the well function.}$$

$$u = \frac{r^2 S}{4Tt} \quad \text{or} \quad S = \frac{4Tu}{r^2} \tag{12.3}$$

where r = distance (in m) between the pumped well and observation well

t = time in days since pumping started

S = storage coefficient (dimensionless)

The application of the Theis equation depends, as does that of the Thiem equation, on several limiting conditions, which must be satisfied. These are as follows:

1. All water must come from storage and the release of water from storage must occur instantaneously upon lowering of the drawdown curve.
2. The aquifer must be horizontal, homogeneous, isotropic, of uniform thickness and infinite in extent.
3. The storage coefficient must be constant.
4. The aquifer must be confined.
5. The well must penetrate the full depth of the saturated aquifer.
6. The diameter of the pumped well must be very small. (The storage in the well can be ignored.)

Although all these conditions are rarely met in nature, the theoretical assumptions implicit in the Theis equation are in most cases satisfied and the formula can, therefore, be successfully applied.

<u>Graphical solution</u>

Firstly, a graph of W(u) versus u, known as a type curve, is prepared on logarithmic paper. Values of W(u) for a wide range of u are available from tables (eg Todd, 1980). The values of drawdown (s) are then plotted against r^2/t on logarithmic paper of the same scale.

The time-drawdown curve is then superimposed on the type curve and moved, keeping the coordinate axes of the two curves parallel (ie the drawdown axis parallel to that of W(u) and the time axis parallel to that of u) until a position of optimum fit of the curves to each other is obtained. A match point is selected from which the values of W(u), u, $\bar{s}$ and r^2/t are read. Then, by substituting them in equations 12.2 and 12.3, the values of transmissivity and storage coefficient are calculated.

The drawdown can be plotted against t when data of the pumping well are used. In this case, the type curve must be turned over to obtain coincidence and, hence, a match point.

b) <u>Cooper-Jacob method</u>

Cooper and Jacob (1946) formulated a graphical solution using a modified formula based on the original Theis equation, which is, in general, applicable to artesian wells and may also be applied to unconfined aquifer wells if the drawdown is sufficiently small. In order to avoid large errors, the straight-line approximation of this method must be restricted to very small values of u (u = 0.02), ie the distance (r) between the pumping well and the observation well is small and the t value is great.

Transmissivity and storage coefficient can then be calculated from the following equations:

$$T = \frac{2.303\ Q}{4\pi\Delta s} = \frac{0.183\ Q}{\Delta s} \qquad (12.4)$$

$$S = \frac{2.25\ Tt}{r^2} \qquad (12.5)$$

where T = coefficient of transmissivity in m^2/day

S = coefficient of storage (dimensionless)

Δs = drawdown difference, in metres, per log cycle of time

t = time at zero drawdown in days

r = distance, in metres, between the pumped well and the observation well

Q = constant rate of abstraction in m^3/day

Graphical solution

Two different straight-lines can be constructed, by plotting the data on semi-logarithmic paper, referring to the time-drawdown and distance-drawdown relationships.

a) In cases where data from only a single observation well or just the pumped well are available, the drawdown (arithmetic scale) is plotted against time (logarithmic scale).

b) If more than one observation well is present, then the drawdown (arithmetic scale) is plotted against t/r^2 (logarithmic scale).

Transmissivity and storage coefficient can be calculated from equations 12.4 and 12.5 given above.

However, if Q is not constant during pumping, instead of the drawdown (s), the specific drawdown (s/Q) is plotted against time (t) or against the ratio t/r^2. In this case, $\Delta s/Q$, which is the difference in specific drawdown per log cycle of time, is used instead of Δs for the calculations.

c) Theis recovery method

The non-equilibrium formula can also apply to the evaluation of the recovery groundwater-level measurements at the end of the pumping tests. The residual drawdown (s') used in this method of calculation equals the difference beween the original groundwater level (prior to pumping) and that measured during the recovery period.

This method is based on the principle that, after the pumping well is shut down, the recovery of the groundwater in that well will be as it would be if the well were being recharged at a rate equal to the mean discharge during the period of pumping. The transmissivity of the aquifer can be calculated independently from the discharge data, although the storage coefficient parameter cannot be calculated by this method.

Transmissivity is given by the equations:

$$s' = \frac{2.303\ Q}{4\pi T} \log \frac{t}{t'}, \text{ or } T = \frac{2.303\ Q}{4\pi \Delta s'} \qquad (12.6)$$

where Q = mean discharge rate in m^3 day

t = time since pumping started in days

t' = time since pumping stopped in days

s' = residual drawdown in m

$\Delta s'$ = residual drawdown over one log cycle of time

Graphical solution

By plotting the residual drawdown (s) on the arithmetic scale of semi-logarithmic paper and the ratio t/t' on the logarithmic scale, the plot should result as a straight line. $\Delta s'$ equals the residual drawdown over one log cycle of time.

The same result is obtained if, instead of the residual drawdown (s'), the drawdown (s) is plotted and, instead of the ratio t/t', time (t') is plotted on semi-logarithmic paper.

12.1.5.3 Results of previous pumping tests

During 1962-63, several pumping tests were carried out as part of the Gold Report (1963) in wells which were constructed for this purpose. The results shown in the report are mostly qualitative (ie description of the well used, discharge during pumping, duration of the pumping test, resultant drawdown) and only in a few cases were the results of the pumping tests analysed and evaluated.

A k-value of 1.2 x 10^{-3} m^2/sec (104 m^2/day) was computed both for the general formation overlying the limestone and for the limestone itself from the results of a test carried out on 7 November 1962 in well 311, sunk in the Sikalia ridge. The report stated that a drawdown of 1.2 m was recorded after 30 minutes of pumping at a discharge rate of 13.6 m^3/h and also that the recovery after pumping ceased was immediate.

A k-value of 10^{-3} m^2/sec (86.9 m^2/day) was calculated for the limestones based on results from well 344 located on the south-western side of aquifer 1. This test will be referred to in the subsequent Section.

The production wells F1 to F5 were constructed in 1970 to supply water to the Electricity Power Station (Units I and II) and the main pumping tests were carried out on these wells during the autumn of 1971. Unfortunately, the results of these pumping tests are not available.

Karkulias (1975) calculated a mean transmissivity value of 395 m^2/h for the narrow area of well F4 (calculated values ranged between 355 and 365 m^2/h for the eight wells employed during the pumping test) and concluded that there is a relative homogeneity in the permeability of the karstic rocks of this area. He also calculated a transmissivity value of 126 m^2/h for the well F5. He noted that recovery to the initial level occurred in both wells within one minute of the end of the pumping.

He reported that, during the main pumping test, all these wells were pumped simultaneously and continuously at a discharge rate of 300 m^3/h for approximately 35 days (30 September 1971 to 4 November 1971). At the end of the pumping test, a permanent lowering ('drawdown') of 1-2 m was recorded in the groundwater level in the wells. It should be noted here that a natural lowering of this range of the groundwater level in aquifer 1 at this time of the year has been established during the present work.

Karkulias also noted that when, after the end of the main pumping test (on 6 November 1971), wells F1 and F3 were pumped at a discharge rate of 415 m^3/h, the groundwater level in all the other wells was also affected.

Finally, he concluded that wells F1 to F5 must be located in the same karstic body, as they reacted in the same manner to the pumping.

Boreholes F6 to F9, F8/72, F10/72 and B were constructed in 1972 to supply water to the Electricity Power Station (Unit III). Pumping tests were carried out for all of these wells during October to December of 1975 by the Hydroerevna Research Company Ltd (1975).

A preliminary step-drawdown test was carried out for each well separately at a discharge rate of 150 m^3/h for the first 3 hours, 300 m^3/h for the next 3 hours and 400-440 m^3/h for the last 3 hours. The main test lasted for about 40 days (30 October 1975 to 9 December 1975) and took place simultaneously in all of these wells at a discharge rate of 300 m^3/h (a few interruptions of up to 4 days were reported after the 20th day of pumping). A final report on these pumping tests was submitted to the Electricity Board by Luttig and Wager (1977) who were responsible for the execution of the pumping tests. In this report, the general conclusions are given and it is also noted that pumping in the wells F6 to F9 does not affect the productivity of the already established production wells F1 to F5. After the main pumping tests, the boreholes F6 to F9 became production wells, while the boreholes F8/72, F10/72 and B proved to be unproductive.

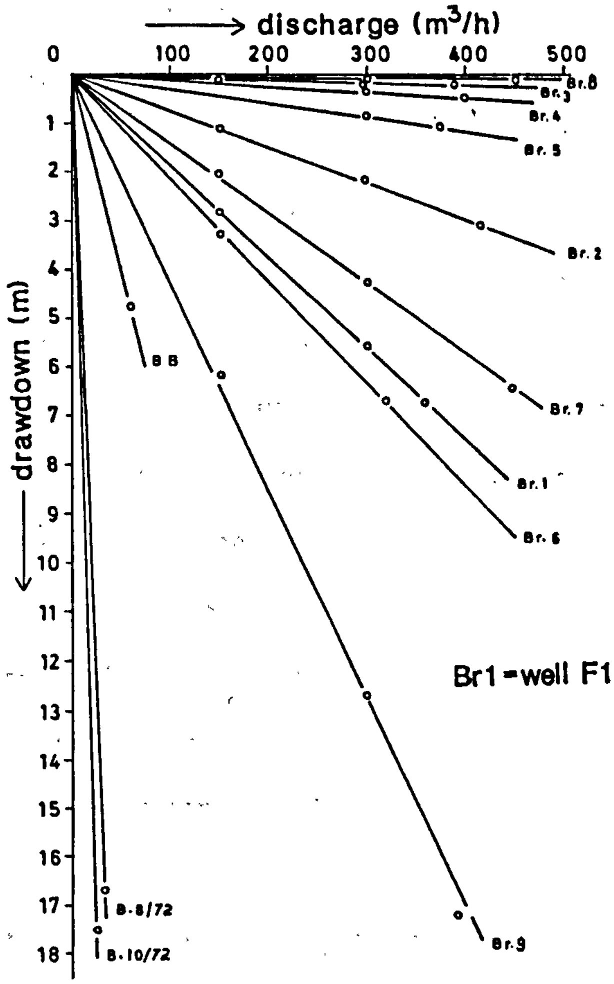


Fig 12.35 Drawdown discharge of the wells sunk in the karstic aquifers developed in the Kyparissia area (after Karkulia, 1975).

Well	F1	F2	F3	F4	F5	F6	F7	F8	F9	F8/72	F10/72	B
Specific productivity $m^3/h.m$	54	135	2300	970	357	47	70	4314	23	12	2	1.4
Transmissivity m^2/day	-	-	-	392	1374	-	126	-	-	0.84	0.30	11

Table 12.4 Hydraulic parameters calculated for the various wells sunk in the karstic aquifers developed in the Kyparissia area (after Karkulias, 1975).

An evaluation of the data obtained from these tests was carried out by Karkulias (1975) (colleague of Lüttig and Wager (*op. cit.*)). He reported that completely different drawdowns were recorded in the various different wells at the end of the main test carried out at the same discharge rate of 300 m^3/h (eg in well F8 drawdown of 0.07 m was recorded, while in well F9 the drawdown was 12.69 m) and concluded that this resulted from the different hydrological-hydrogeological conditions prevailing in the area. The results of the pumping tests carried out in the wells F1 to F9, F8/72, F10/72 and B are shown in Figure 12.35, while the values of the various hydraulic parameters calculated by Karkulias based on the results of the tests are given in Table 12.4. He noted that a lack of homogeneity exists in the karstic aquifers developed in the Kyparissia area, although the values calculated are not representative of the whole of the karstic body as they only give a statistical indication of the hydrological regime of the area.

12.1.5.4 Interpretation of the pumping tests

The results of the primary and also the main pumping tests carried out in wells F6 to F9 were available to the author. Detailed re-analysis of the pumping test data were not undertaken, for the main aim of the present work was to study the development and extent of the karstic aquifers and to establish their recharge sources in the Kyparissia field, rather than to study their hydraulic properties. As the karstic aquifers developed here are to be dewatered in order to permit mining of the lignite, they do not constitute a potential water source.

The data for well P1 were, however, evaluated, in order to obtain an idea of the permeability and storability of the karstic aquifers. This well was sunk in 1975 at the western border of the Kyparissia field, in the confined part of aquifer 1, in order to investigate the groundwater conditions of the karstic limestone in this area (Fig 12.3).

Two tests were carried out during the late spring/summer 1975:

a) a preliminary one between 16 May 1975 and 20 May 1975, and

b) the main one between 3 June 1975 and 14 June 1975.

Wells 342, 343, 346, P7 and P8 were used as observation wells.

Well P1

Upper end of the casing pipe: at an elevation of 348.63 m.

Total depth: 95.0 m (0-43.3 m: basin sediments; 43.3-49.0 m: gravel formation and 49.0-95.0 m: solid limestones)

Casing: 250 mm (down to a depth of 49.0 m)

Diameter of the well: 170 mm (from a depth of 49.0 m to 95.0 m)

a) The preliminary test was carried out between 16 and 20 May 1975 and lasted for 98.5 hours with two interruptions on the third day (18 May 1975), the first lasting 6.15 hours and the other half an hour. The rate of discharge averaged 40.8 m^3/h during the first 39 hours and 45.9 m^3/h during the rest of the time.

   The initial piezometric surface (ie on 16 May 1975) was at an elevation of 333.93 m. The drawdown, which was kept at an average depth of 40 m below the upper end of the casing pipe (ie at an elevation of 308.63 m) averaged 25.3 m. The groundwater level rose to 325.63 m during the first interruption and to 326.08 m during the second. At the end of the test, the drawdown in well P1 was 25.3 m and was as follows in the observation wells: 342 = 1.2 m; 343 = 2.2 m and 346 = 0.3 m.

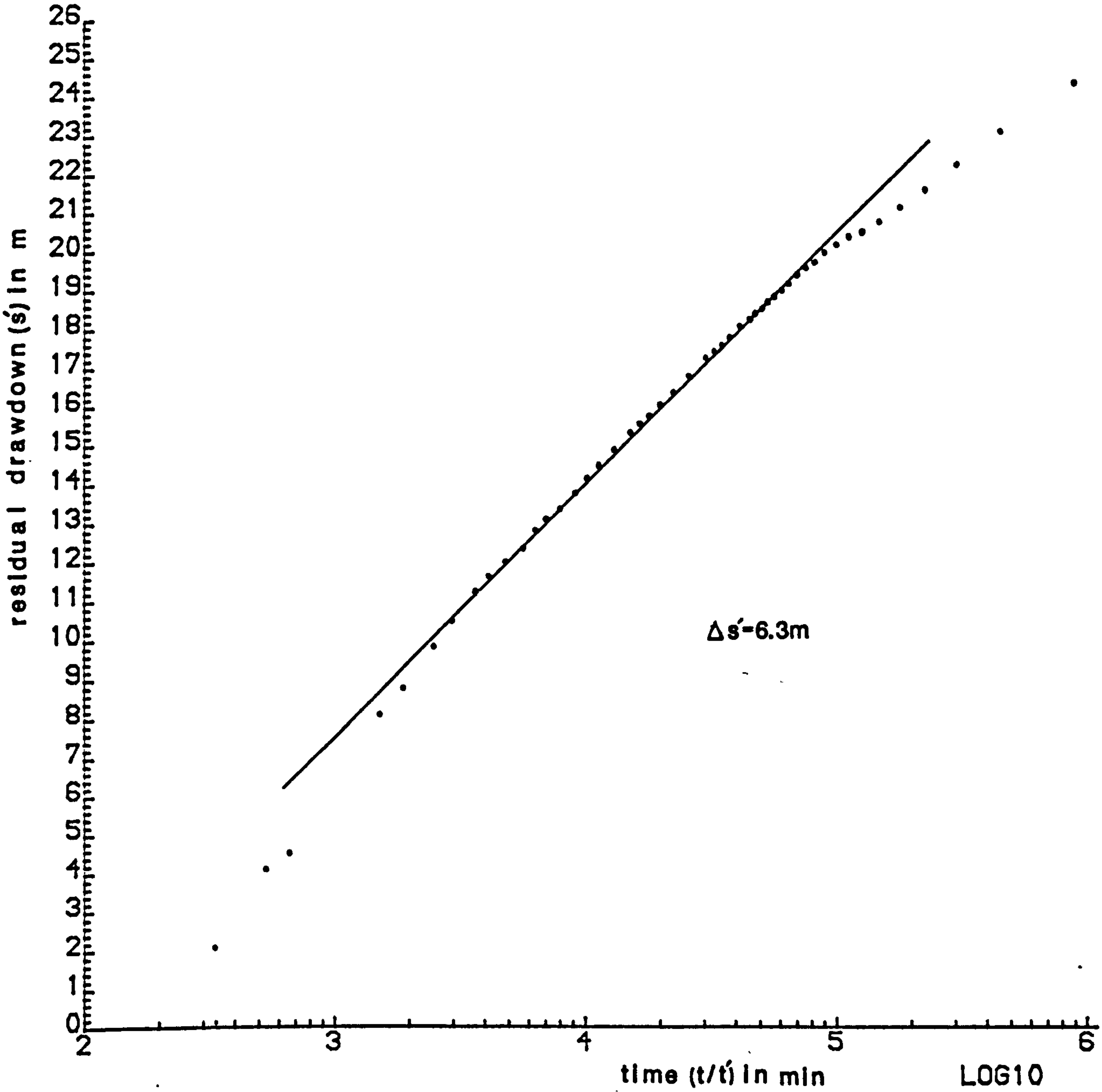
b) The main step-drawdown was carried out between 3 June 1975 and 14 June 1975 and lasted for 258 hours. The average rate of discharge was 50.9 m^3/h.

The initial piezometric surface was at an elevation of 333.95 m. The drawdown was kept steady for the first 42 hours, being on average 25.3 m (40 m below the upper end of the casing pipe) and was also kept steady during the rest of the time at a lower average depth of 44.4 m below the upper end of the casing pipe, representing a drawdown of approximately 29.7 m. After the pumping had stopped, recovery data were taken.

The results obtained from the main pumping test, both for the pumped well and for the observation wells, were analysed using the Cooper and Jacob method (1946) (ie, by plotting the drawdown (s) against the logarithm of time (t) (Figs 12.36 and 12.39). The recovery data were evaluated by plotting the residual drawdown (s') against the logarithm of the ratio t/t' (Fig 12.40).

The transmissivity values calculated for the area in which well P1 is sunk range between 26 and 170 m^2/day. The values differ greatly from one well to another. The same applies to the storage coefficient values which were calculated to be between 0.0001 and 0.02. These variations are not considered to be due to an anisotropy of aquifer 1 but, rather, to the presence of different hydrogeological boundary conditions within the extent of the aquifer on opposite sides of well P1, ie the presence of a recharge area to the east of the pumping well and an impermeable barrier to its west.

From Figures 12.37 to 12.40, it can be seen that, even after 258 hours of continuous pumping, no steady flow to the pumping well was established, as the drawdown continued to increase.



Recovery

Pumped well P1

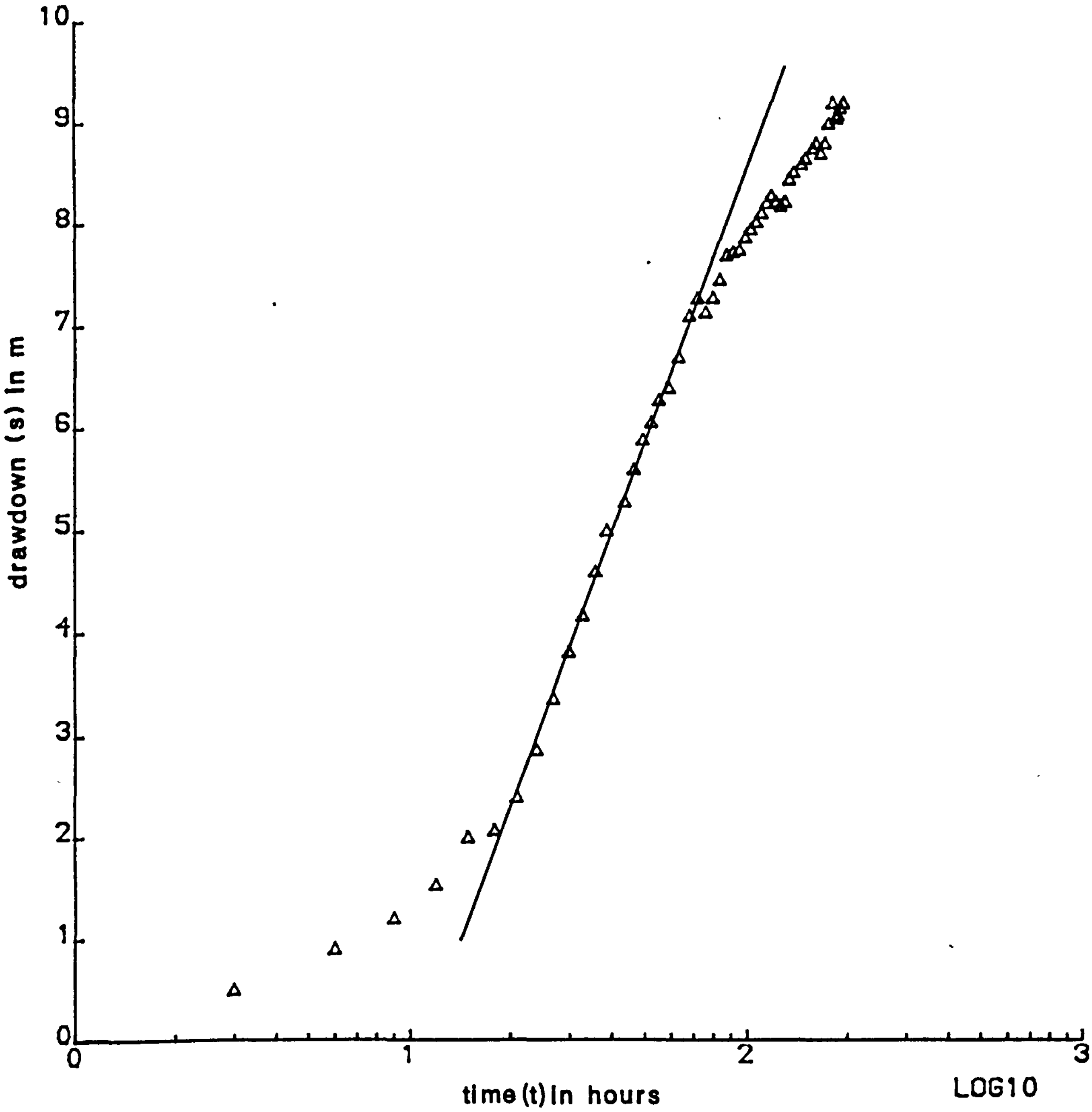
Q (mean) = 50.9 m^3/h = 1221.6 m^3/day

$\Delta s'$ = 6.3 m

$$T = \frac{Q}{4\pi\Delta s'} = \frac{1221.6\ m^3/day}{4\pi \times 6.3\ m}$$

$$= 35.3\ m^2/day$$

Fig 12.36 Evaluation of the recovery data of the well P1.



<u>Pumping test</u>

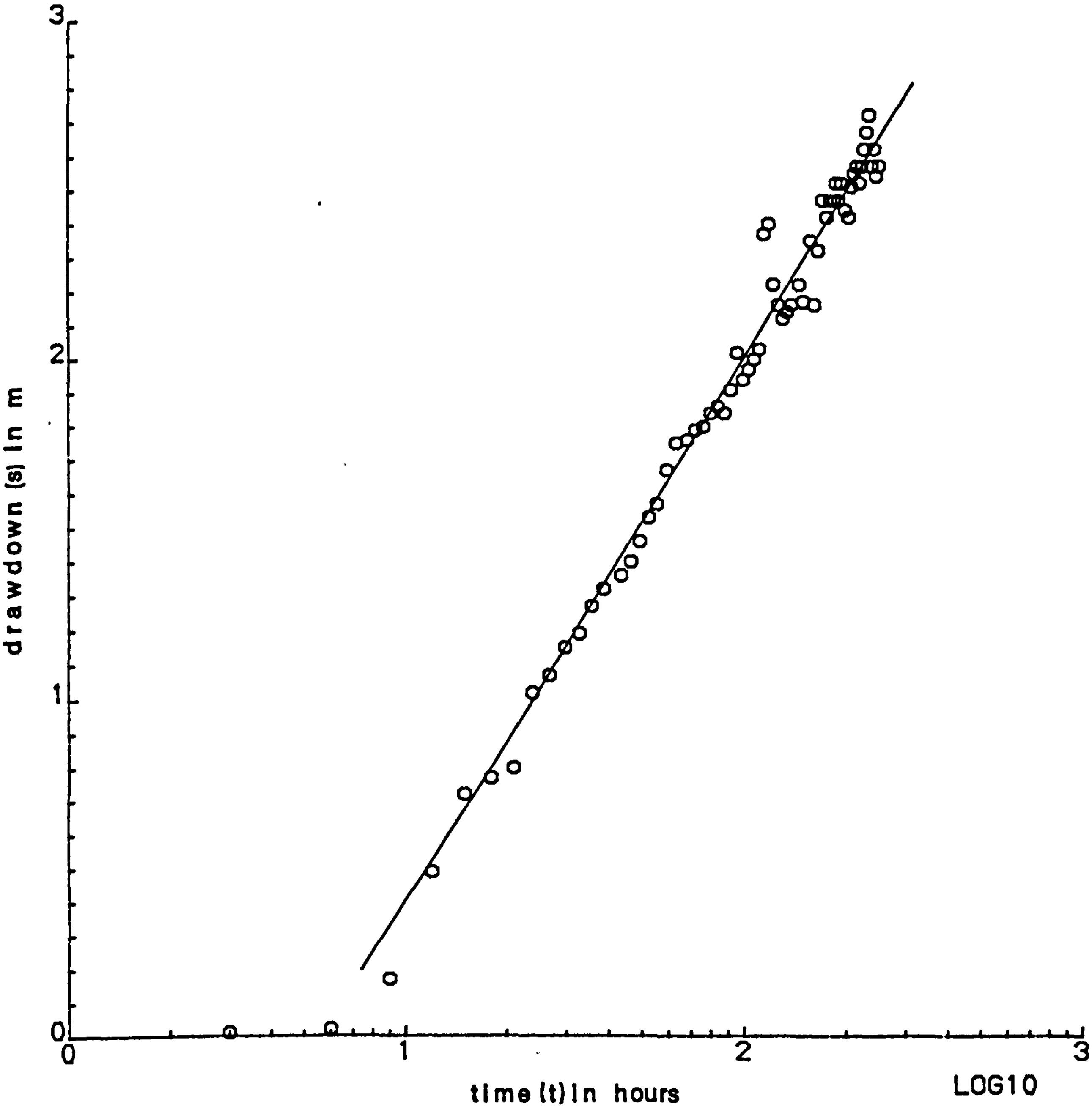
<u>Observation well P7</u>

Q (mean) = 50.9 m^3/h = 1221.6 m^3/day
Δs = 8.4 m
to = 10.1 hours = 0.42 days
r = 125 m

$$T = \frac{2.3\ Q}{4\pi\Delta s} = 26.6\ m^2/\text{day}$$

$$S = \frac{2.25\ T\ to}{r^2} = 0.0016$$

Fig 12.37 Evaluation of the pumping test data of the observation well P7.



<u>Pumping test</u>

<u>Observation well 342</u>

Q (mean) = 50.9 m^3/h = 1221.6 m^3/day

Δs = 1.54 m

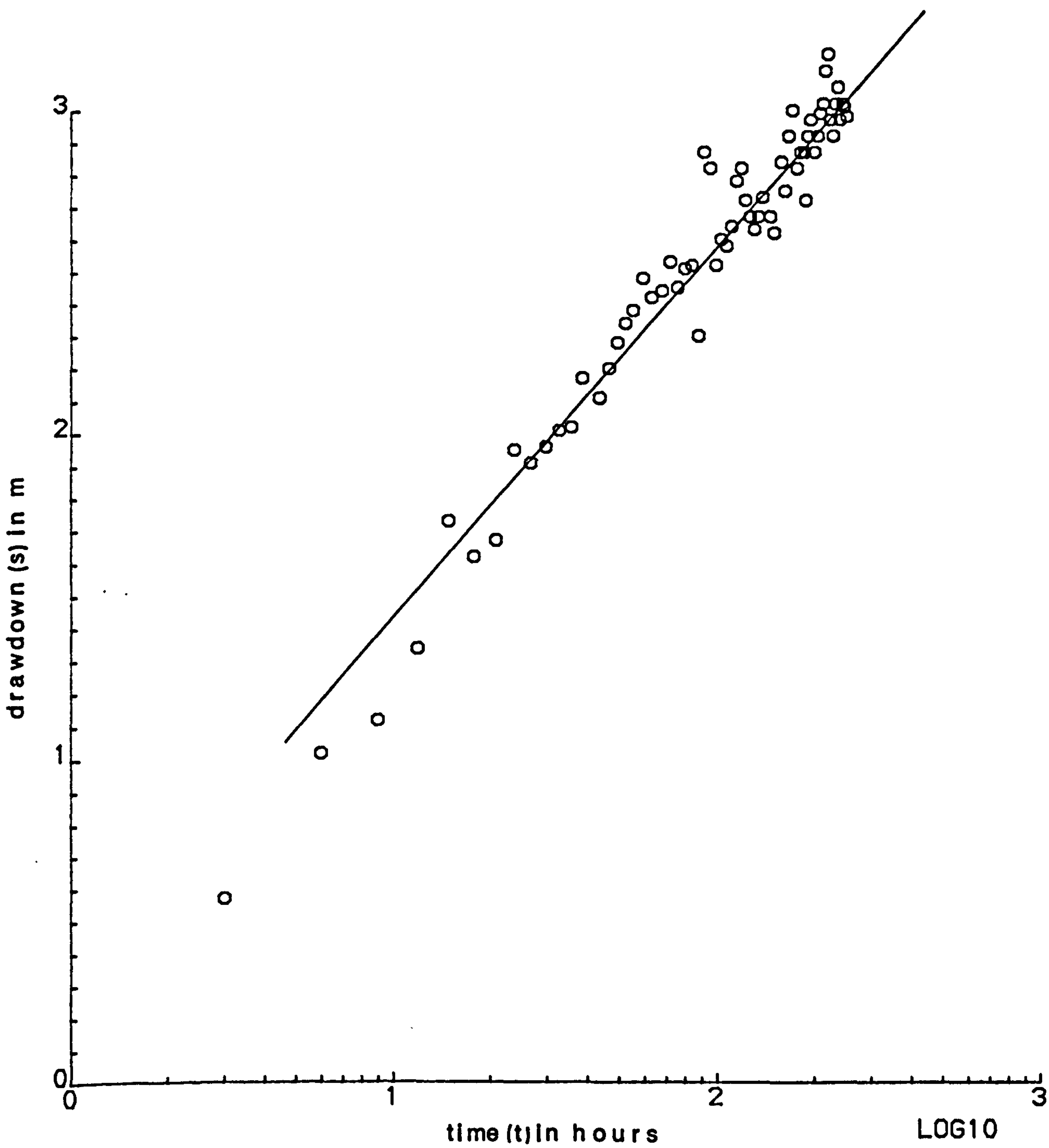
to = 5 hours = 0.2 days

r = 185 m

$$T = \frac{2.3\ Q}{4\pi \Delta s} = 145.26\ m^2/\text{day}$$

$$s = \frac{2.25\ T\ to}{r^2} = 0.0019$$

Fig 12.38 Evaluation of the pumping test data of the observation well 342.



<u>Pumping test</u>

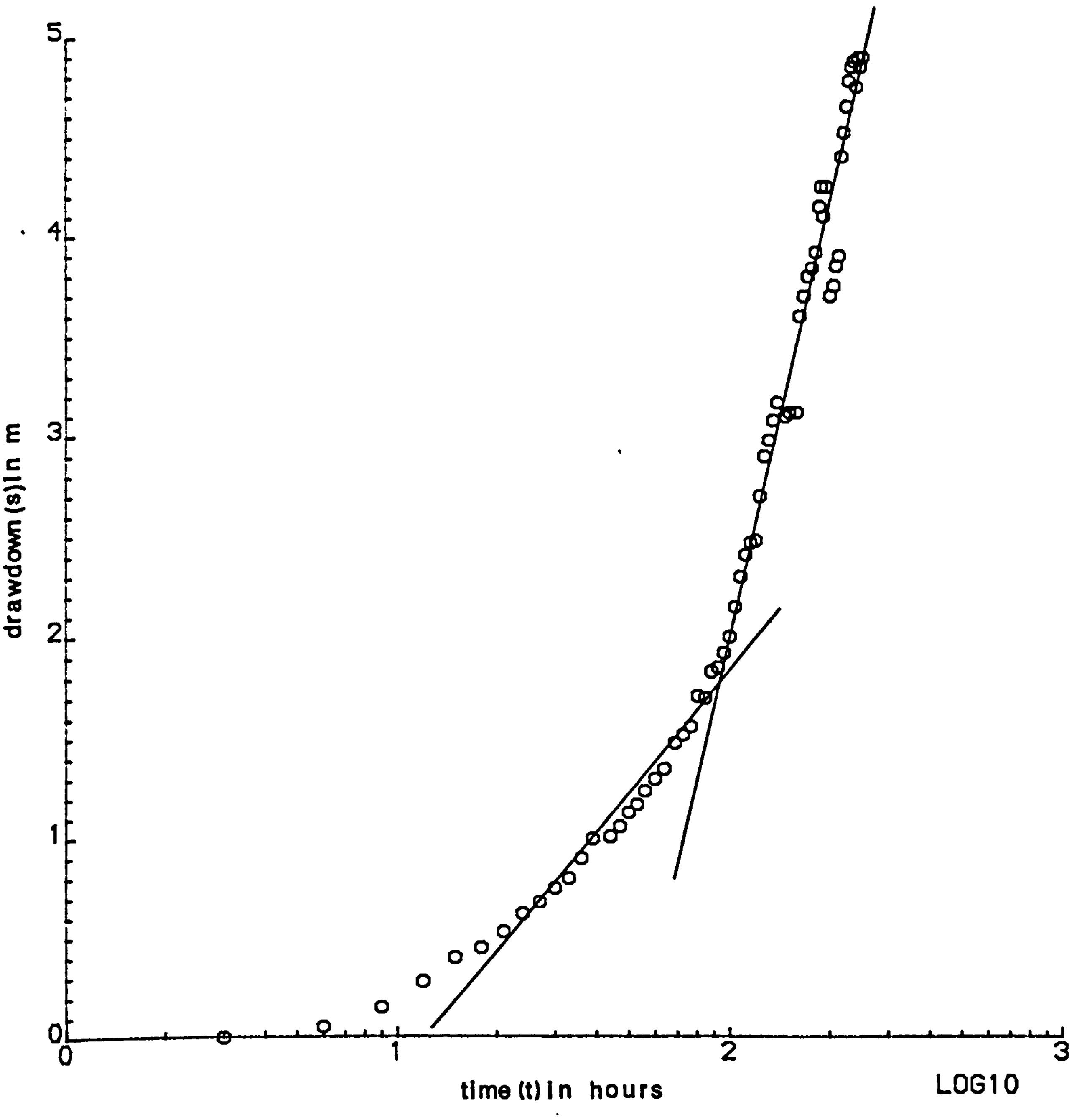
<u>Observation well 343</u>

Q (mean) = 50.9 m^3/h = 1221.6 m^3/day
Δs = 1.33 m
to = 18 min = 0.01 days
r = 180 m

$$T = \frac{2.3\ Q}{4\pi \Delta s} = 168.1\ m^2/day$$

$$S = \frac{2.25\ T\ to}{r^2} = 0.00012$$

Fig 12.39 Evaluation of the pumping test data of the observation well 343.



Pumping test

Observation well P8

Q (mean) = 50.9 m^3/h = 1221.6 m^3/day
Δs = 2.15 m
to = 10.1 h = 0.42 days
r = 175 m

$$T = \frac{2.3\ Q}{4\pi \Delta s} = 104.0\ m^2/day$$

$$S = \frac{2.25\ T\ to}{r^2} = 0.0032$$

Fig 12.40 Evaluation of the pumping test data of the observation well P8.

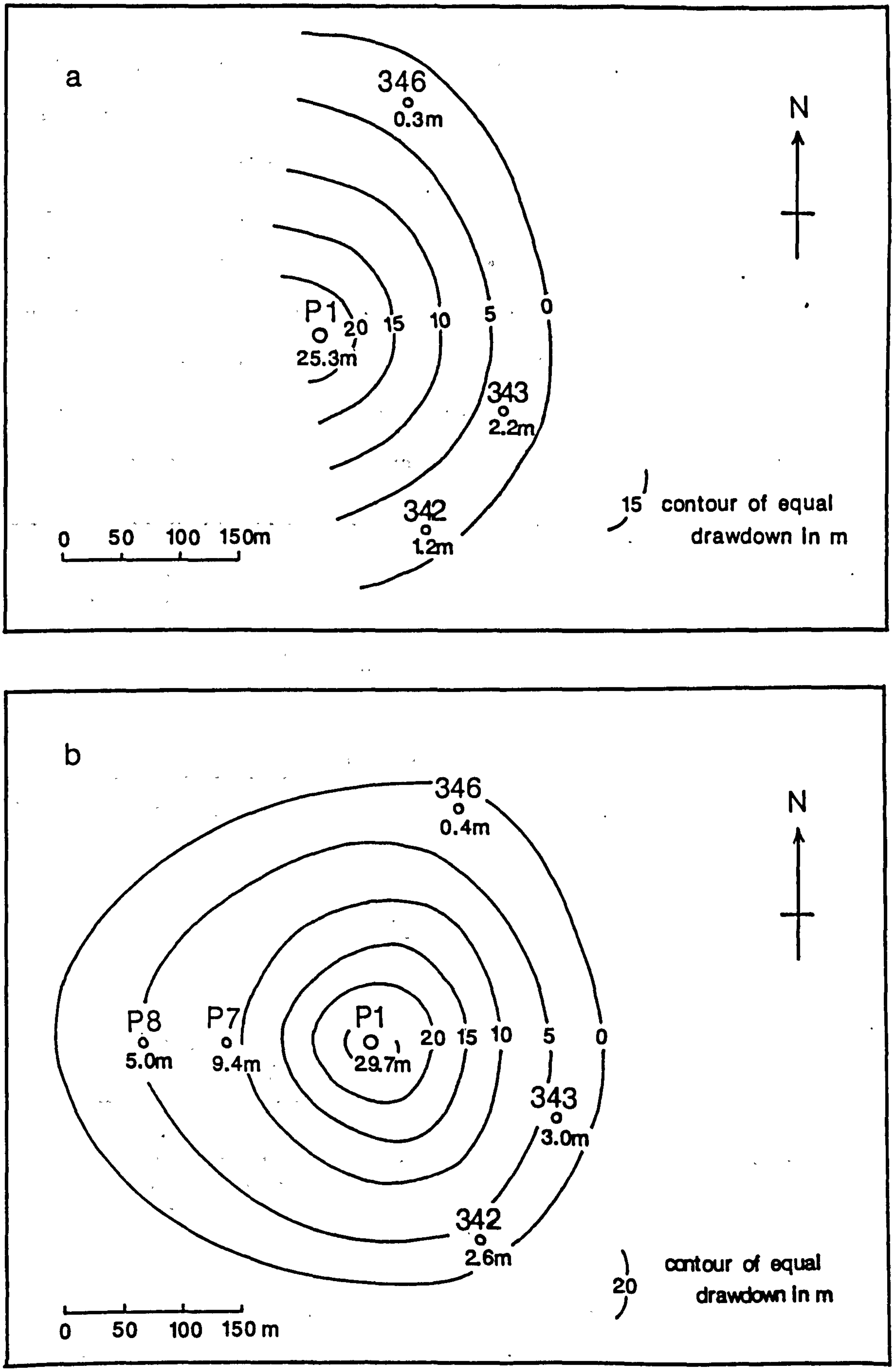


Fig 12.41 Areal distribution of the drawdowns at the end of both the pumping tests in the well P1
a) preliminary pumping test (16/5/75 to 20/5/75), and
b) main pumping test (13/6/75 to 14/6/75).

The areal distribution of the drawdown at the end of both the preliminary and the main tests is shown in Figure 12.41. It can be seen that, at the end of the main test, the cone of depression was developed predominantly in a westward direction.

Fig 12.42 shows the gradual development of the cone of depression in a westerly direction during the main pumping test. It can be seen that the cone of depression only extended westwards during the pumping. This indicates the presence of a water barrier on the western side of the well and the presence of a recharge boundary on its eastern side.

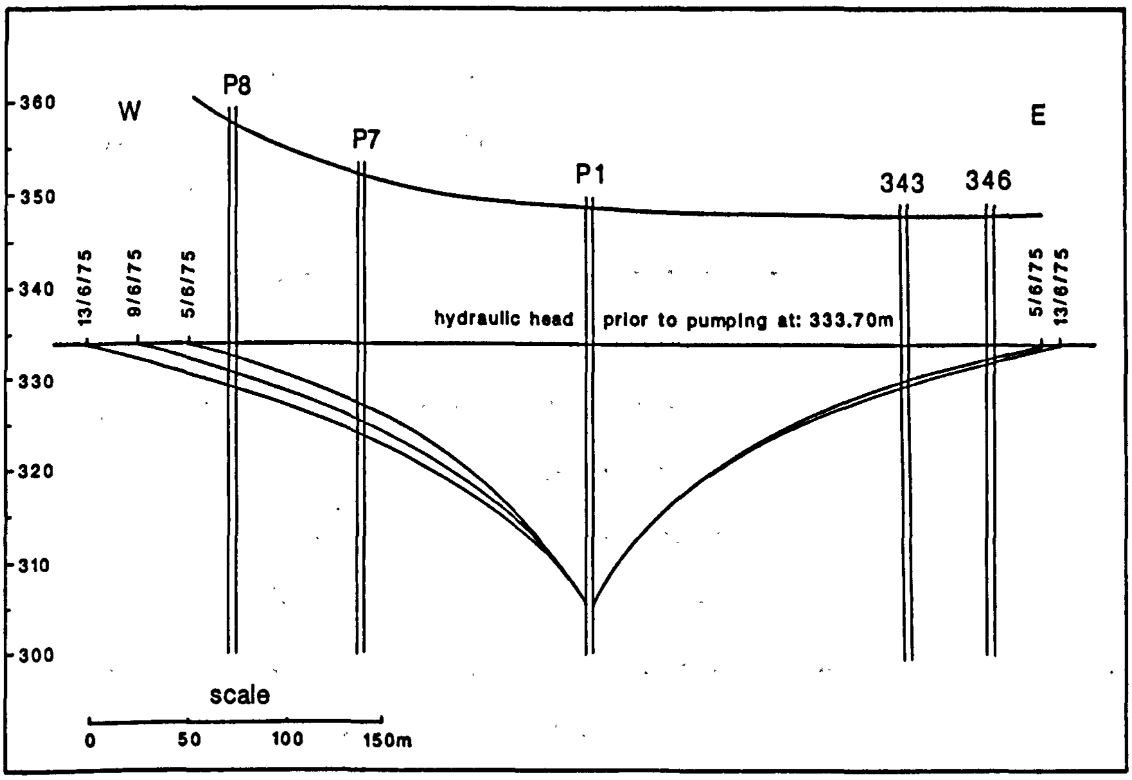


Fig 12.42 Cross-section of the area of pumping well P1. A gradual extension of the cone of depression in an almost exclusively westerly direction occurred during the main pumping test (3 June 1975 to 14 June 1975).

Two tests each lasting 24 hours, carried out in well 344 on 30 and 31 November 1963 and 5 and 6 February 1963, are reported in the Gold Report (1963). The wells 341, 342, 343, 345 and 346 were used as piezometers.

Well 344

Upper end: at an elevation of 344.77 m

Total depth: 148.0 m (0-106.8 m: basin sediments; 106.8-113.2 m: gravel formation and 113.2-148.0 m: limestones)

Casing: 250 mm (down to a depth of 106.9 m)

Diameter of the well: 170 m (from a depth f 106.9 m to 148.0 m)

In the second test, with a discharge of 90 m^3/h, a drawdown of 25 m was obtained in well 344 which was being pumped, while the drawdown measured in the observation wells was as follows:

341 = 0.05 m; 342 = 0.35 m; 343 = 2.5 m; 345 = 0.0 m and 346 = 0.05 m. Based on the results obtained from this pumping test, a k-value of 87 m^2/day was computed (Gold Report, 1963).

In Figure 12.43 the measurements of the recorded drawdown at the end of the pumping test in well 344 and the observation wells are shown, firstly as an areal distribution of the cone of depression resulting from the pumping (a) and secondly on the cross-section along the line A-A' (b). From this Figure, the conclusion can be drawn that, if the aquifer is considered to be relatively homogeneous and isotropic, then the direction of water flow is from a north-easterly direction and this indicates that the area around the Kyparissia bridge over the Alfios must represent the recharge area of aquifer 1.

Pumping tests of wells F1 to F5, F8 and F9

These seven production wells are located within aquifer 1 and were constructed to supply water to the Electricity Power Station, as mentioned earlier. During the main pumping tests, all these wells were pumped at a constant discharge rate of 300 m^3/h over a long period. The resultant drawdowns for each of the wells at the end of the pumping tests are listed in Table 12.5.

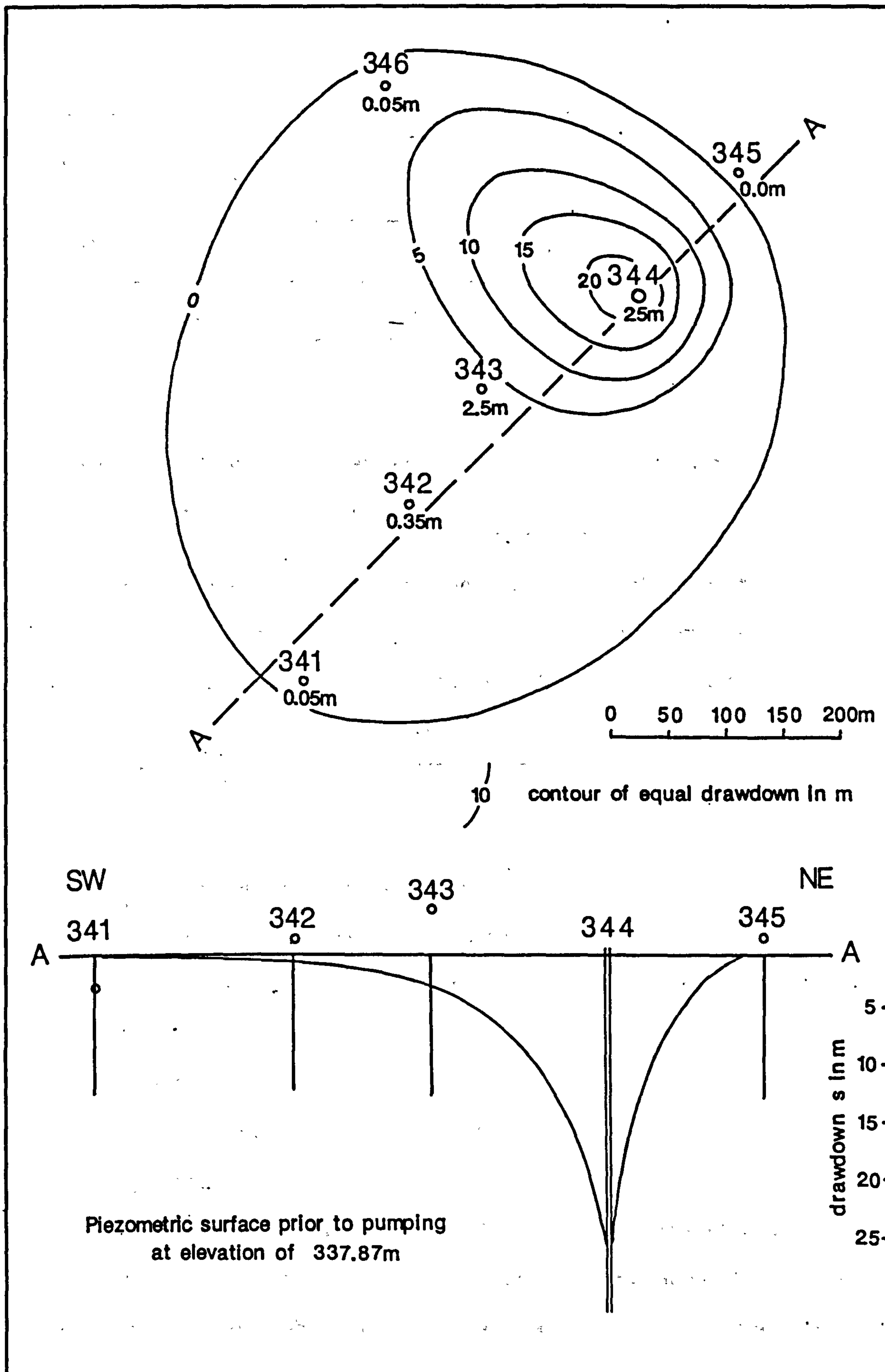


Fig 12.43 a) Areal distribution of the drawdowns recorded in the wells at the end of the pumping test in well 344, and
b) Cross-section along the line A-A'.

well	F1	F2	F3	F4	F5	F8	F9
discharge in m^3/h	300	300	300	300	300	300	300
drawdown	5.54	2.15	0.13	0.31	0.84	0.07	12.69

Table 12.5 Drawdown in wells F1 to F5, F8 and F9 measured at the end of the main pumping test.

According to the Thiem (1906) equilibrium formula (12.1) which can be applied in the case of steady radial flow to a well, the drawdown (s) is given by the equation: $s = h - h_w = \frac{Q}{2\pi kb} \ln \frac{r}{r_w}$ (12.6)

Based on the Thiem formula, the equation which gives the drawdown in a well (s_w) pumping at a discharge rate Q, when there is a discharging well in the same aquifer at a distance r (Davis & de Weist, 1966), is:

$$s_w = h - h_w = \frac{Q}{4\pi kb} \ln \frac{(r-r_w)^2}{r_w^2} = \frac{Q}{2\pi kb} \ln \frac{r}{r_w} \qquad (12.7)$$

where s_w = drawdown in the well in m

h = initial piezometric level in m

h_w = hydraulic head, in m, in the well at the end of the pumping test

k = hydraulic conductivity in m^2/day

b = thickness of the aquifer in m

r_w = radius of the well in m

In the case of transmissivity of the aquifer remaining unaltered (ie k and b constant) throughout its extent, then, according to equation 12.7, the drawdown which will be recorded in wells of the same radius pumped at the same discharge rate, is proportional to their distance (r) from the discharge well.

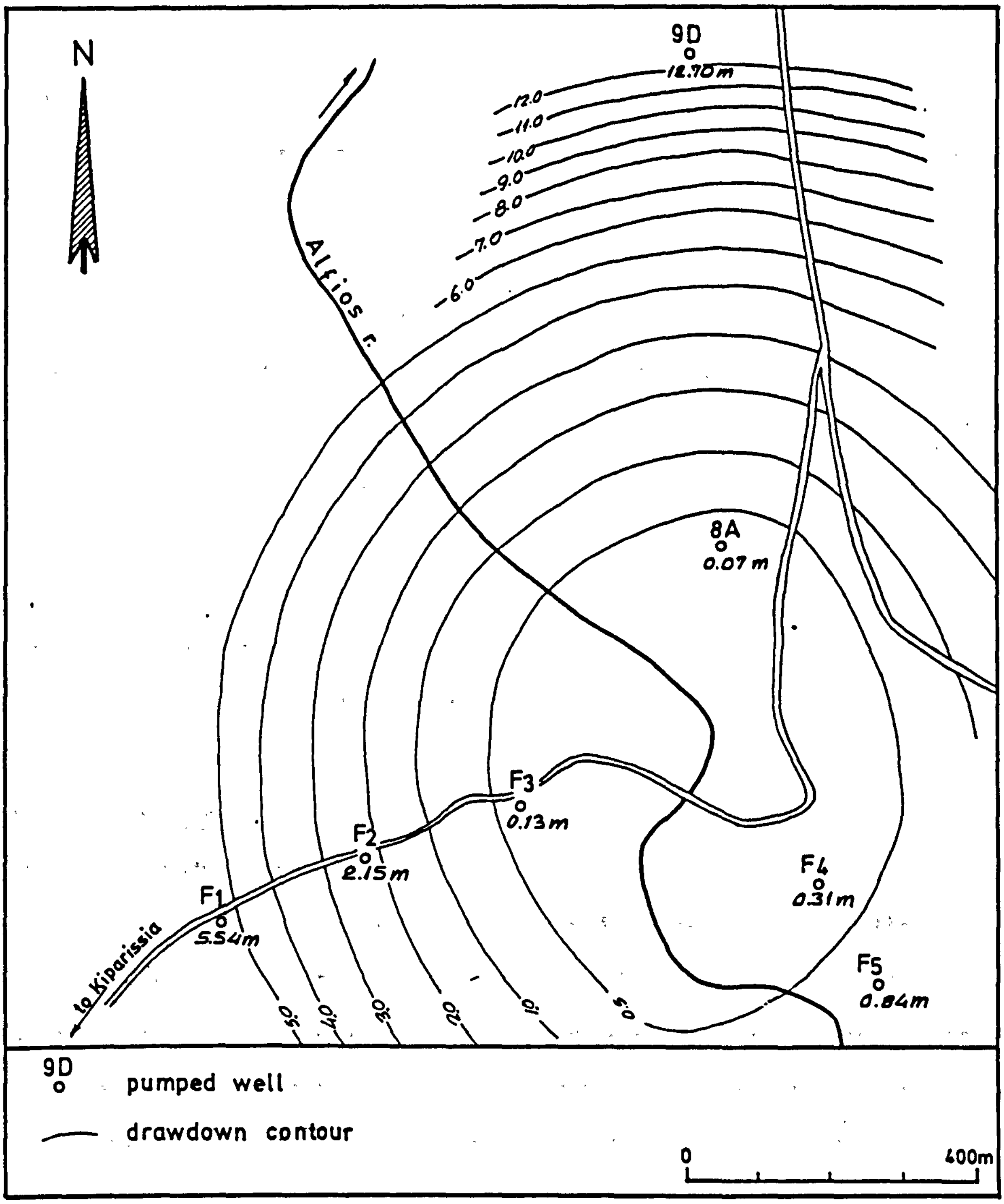


Fig 12.44 Areal distribution of the drawdowns recorded in the wells F1 to F5, F8 and F9 (sunk in aquifer 1) when each was pumped at a discharge of 300 m^3/h.

The part of aquifer 1 covered by wells F1 to F5, F8 and F9 can be considered, due to its small area, not to exhibit great differences in transmissivity throughout its extent and the first condition is therefore satisfied. During the main pumping tests, all the above wells, which are of the same type of construction and hence of the same radius, were pumped at a steady discharge rate of 300 m^3/h. After a period of 70 days of almost continuous pumping (with just a few interruptions of up to a few hours), a steady flow to the wells should have been established. As the various conditions on which the application of equation 12.7 is dependent should now all be satisfied, it may be concluded, according to this equation, that the drawdown caused by pumping must be proportional to the logarithm of the distance from the discharging area. This is shown graphically in Figure 12.44, where the concentric equipotential lines of equal drawdown are drawn logarithmically around the Kyparissia bridge over the Alfios. This establishes that, during the dry season, aquifer 1 recharges exclusively from the Alfios river, percolating through the area around the Kyparissia bridge.

12.2 Aquifer 2

12.2.1 Introduction

Aquifer 2 is a small karstic aquifer developed on the northern side of the wider area of the Kyparissia field (Fig 11.8). It is developed within a small, overturned limestone body with limited outcrop, forming the Aghios Georgios gorge and partly covered by the unconsolidated basin sediments (Fig 12.45). Hence, for the greater part of its extent, it is unconfined and only in places is it confined by the relatively impermeable basin sediments, mainly the Apiditsa stage and the Marathousa beds.

The Alfios river runs over the whole extent of the limestone outcrop, crossing it along a distance of approximately 250 m and at an elevation of approximately 329-330 m. In places, only a thin, recent gravel body lies on the river bed while, for a short distance on the southern side of the limestone outcrop, a relatively thicker gravel body of the older river terrace lies between the river and the limestone. In these areas, direct hydraulic continuity exists between the Alfios river and aquifer 2.

Alfios river water percolating into this aquifer is the predominant recharge source, as the amount of water originating from precipitation infiltrating over the limited outcrop is considered to be negligible. In addition, part of the recharge water originates from the superficial aquifer developed in the terrace gravel-bodies occurring upstream from the Aghios Georgios gorge. These bodies wedge out just before the Aghios Georgios gorge. Part of the water seasonally retained in these bodies returns to the Alfios river during the dry season. The amount of water derived from the gravel bodies at this point, was measured at the end of September 1962 to be 0.088 m^3/s (316 m^3/h), (Gold Report, 1963).

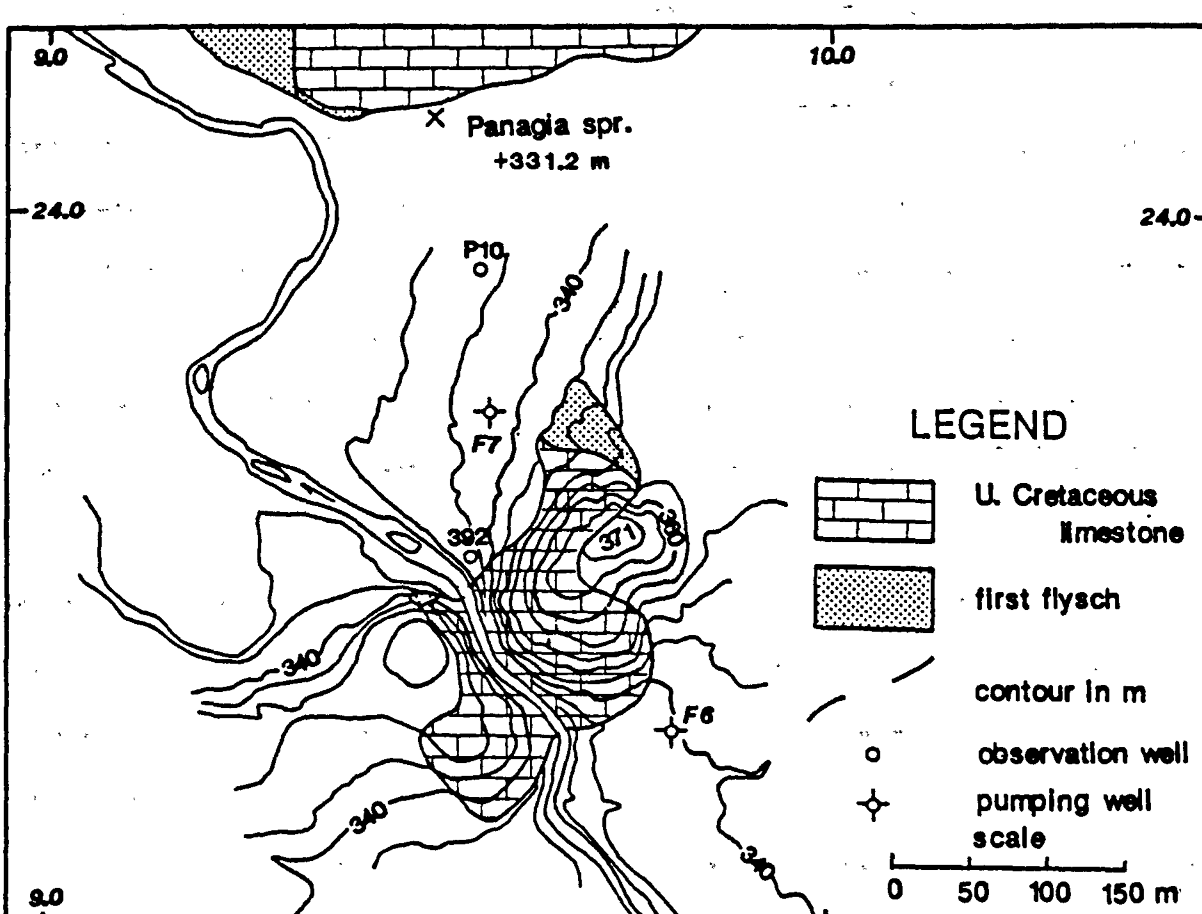


Fig 12.45 Topographic and geological map of the Aghios Georgios gorge area north of the Kyparissia field (aquifer 2).

Points of natural discharge of this aquifer have not been observed. Two productive wells (F6 and F7) were sunk in aquifer 2 to supply water to the Power Station (Unit III). They each have a capacity of 250 m^3/h and, since 1974, their operation has been fairly continuous. In addition to the productive wells F6 an F7, two observations wells, the boreholes 392 and P10, were sunk into aquifer 2 (Fig 12.45).

Measurements of the groundwater levels of aquifer 2 exist for the period 1975-81 for all these wells. The well hydrographs and groundwater contour-maps of this aquifer were drawn using these data.

12.2.2 Groundwater levels

12.2.2.1 Well hydrographs

The common point of the hydrographs of the wells of aquifer 2 is that the recorded groundwater level, ie the rest water level for the production wells F6 and F7, does not show any significant regular short-term or long-term, ie seasonal or annual, fluctuations. The groundwater level of this aquifer is relatively constant, lying at an elevation of 326-329 m and only in a few cases was a lower water table/ piezometric surface recorded in places, at an elevation of 324-325 m. The irregular, short-term fluctuations occurring on the hydrographs are due to the pumping of the production wells (F6 and F7) which, due to the relatively small extent of aquifer 2, influences the form of the whole water table/piezometric surface. The resulting drawdowns were also recorded in the observation well P10 and, to a lesser extent, in the observation well 392.

The observation well 392, which is drilled just a few metres away from the bed of the Alfios river, has a rather flat hydrograph (Fig 12.46). The water table level in this observation well lies at an average elevation of 327 m (325-329 m).

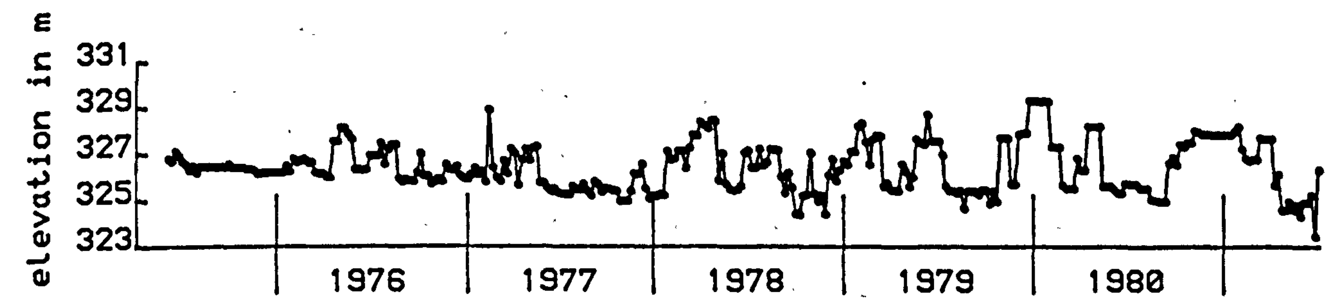


Fig 12.46 Hydrograph of well 392 sunk in aquifer 2.

The small fluctuations, ranging from zero to approximately 2 m, from the mean level of 327 m are due mainly to the influence of the pumping of the production wells F6 and F7. For most of the observation period, a clearer influence of the abstraction of water and the resulting drawdown at the well F6 can be recognised on the hydrograph of well 392. Another factor responsible for the small fluctuations present in well 392 could be the fluctuations in the discharge rate of the Alfios river.

The small drawdowns recorded in the hydrograph of well 392 generally occur during periods of a reduced rate of run-off of the Alfios river, which may possibly be associated with a decrease in the permeability of the river bed in the area adjacent to well 392. Under these conditions, the recharging water can only just balance the high abstraction from the production wells and the cone of depression will reach even well 392, close to the river.

In the hydrographs of the production wells F6 and F7 (Figs 12.47 and 12.48), two completely different water table levels can be recognised. A higher one, referred to as the non-pumping or rest water level and a lower one, the pumping level, measured when the wells are in operation. The non-pumping or rest water level of each well is always found to lie at a certain, almost constant, elevation and does not show any regular significant short-term or long-term fluctuations, either seasonal or annual.

The lower or pumping level of each well, although not so stable, tends to lie at a certain depth below the rest level. This depth depends on the distance of the well from the recharge source, ie the Alfios river, on local factors such as the heterogeneity in permeability of the aquifer, on changes in the permeability of the aquifer, eg as may result from the sealing of certain channels feeding it and, finally, on seasonal factors such as the run-off rate of the Alfios river.

Thus, the upper or rest water level of well F6 lies at an elevation of 326-328.5 m, while the lower or pumping level of this well tends to stabilise at a height of 318-321 m (Fig 12.47). During the period from May 1977 to January 1978, and also in a few other cases, a greater drop of the lower or pumping level down to an elevation of 315-317 m, or even a little lower (312-314 m), was recorded. This could most possibly be due to a decrease in the flow of the Alfios river as a result of relatively low precipitation during this particular period.

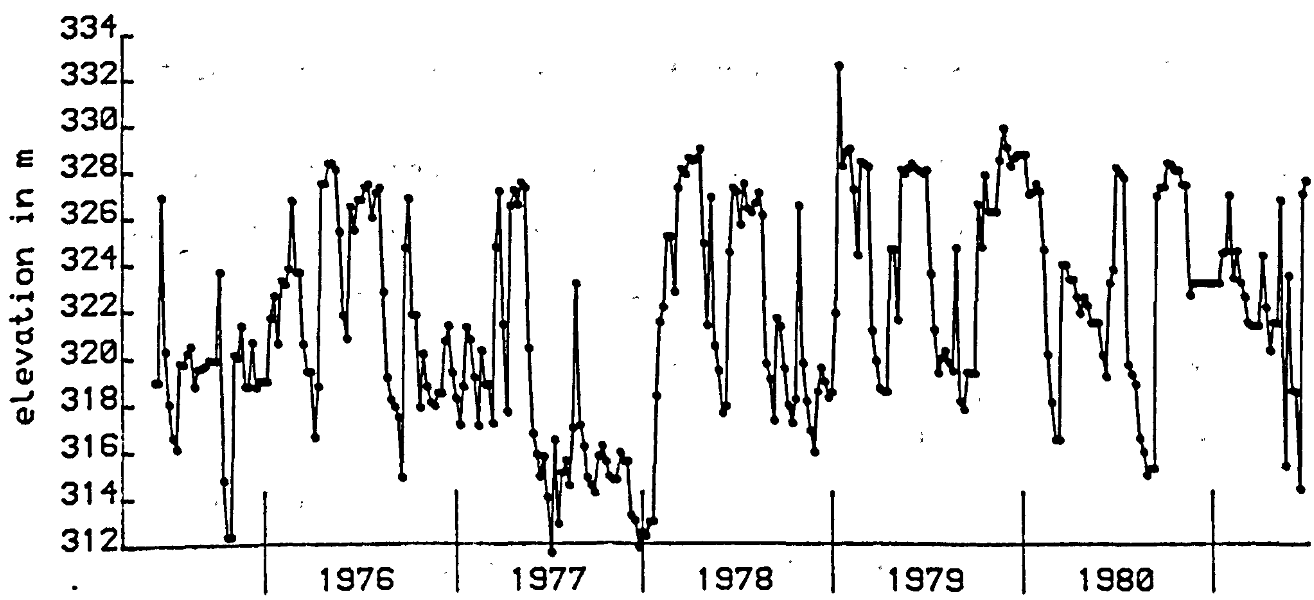


Fig 12.47 Hydrograph of the production well F6, sunk in aquifer 2.

The upper or rest water level of well F7 is more constant, lying at an elevation of approximately 326 m (Fig 12.48). The six measurements considerably higher than this value must be considered erroneous. The lower or pumping level of well F7 tends to stabilise at the same height as that of well F6, namely at an elevation of 318-320 m or slightly lower. Generally, the lower pumping level of Well F7 is more constant than that of well F6, which is situated closer to the Alfios and is therefore greatly influenced by the changes in the Alfios discharge rate.

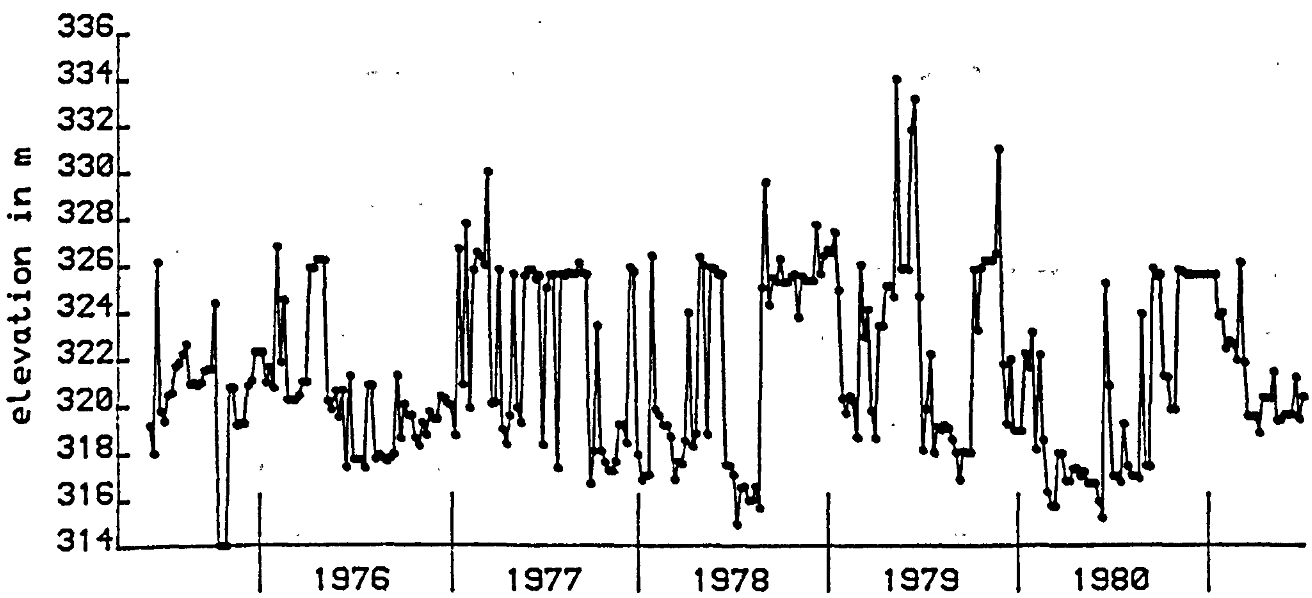


Fig 12.48 Hydrograph of the production well F7, sunk in aquifer 2.

The hydrograph of well P10 also shows an absence of detectable, regular, short or long-term fluctuations. An upper or rest water level can also be recognised, lying at an elevation of between 325.5 and 327.5 m and most usually at an elevation of approximately 326 m. A few measurements departing greatly from these values were considered false (Fig 12.49). The irregular fluctuations of up to 7.0 m below the upper or rest water level are due to the pumping of the production wells F6 and F7. A closer response to the drawdowns recorded in well F7, situated on this side of the aquifer, is distinguishable in the fluctuations recorded in well P10.

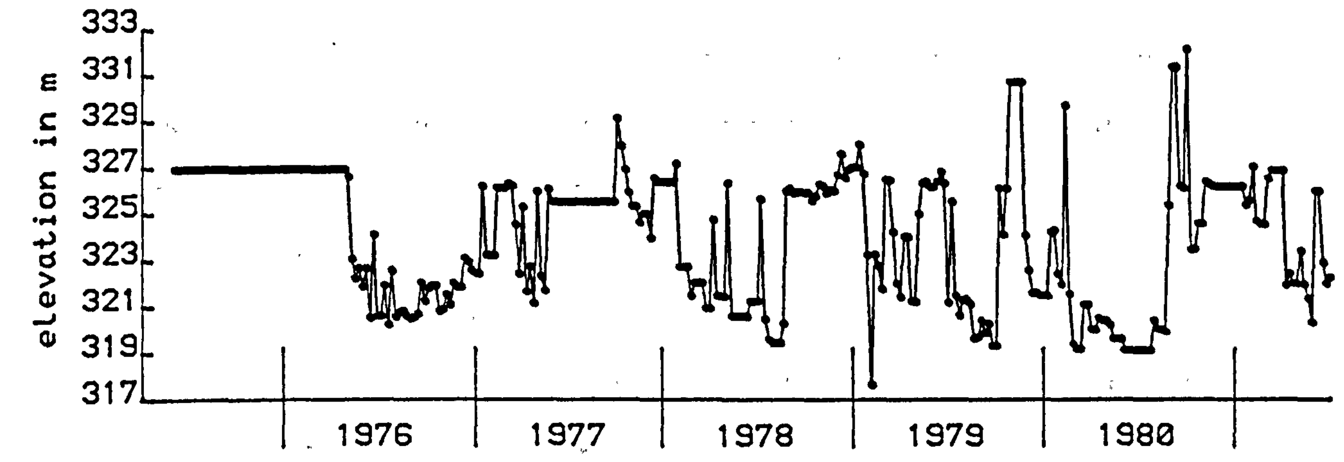


Fig 12.49 Hydrograph of the well P10 sunk in aquifer 2.

12.2.2.2 Groundwater contour-maps

Maps of the groundwater levels or groundwater contour-maps were also drawn for aquifer 2. These maps were prepared to a scale of 1:5,000, in a similar way to those for aquifer 1, for each year of the observation period (1975-81) (Figs 12.50 and 12.56).

The rest water or non-pumping water table/piezometric surface of aquifer 2 does not exhibit any regular fluctuations, even of a small range. The groundwater contour-maps do not, therefore, correspond to a 'lower' or 'higher' groundwater surface of aquifer 2. They were drawn for those dates of each year on which the lower and higher water table levels occurred in aquifer 1 and were constructed for comparative purposes only. The groundwater levels recorded in aquifer 2 on these dates are also noted in Appendix III.

Thus, when aquifer 2 is not pumping (ie when neither of the production wells F6 and F7 is in operation), a generally small hydraulic gradient directed from the Alfios river towards the aquifer exists, eg during 1979 (Fig 12.54). The form of the water table/piezometric surface for 1979 indicates that, under natural conditions, the Alfios river is the recharge source for aquifer 2 and, further, that discharge takes place from the northern part of aquifer 2 where the observation well P10 is situated.

As no springs of any significant discharge rate or other groundwater flow points were detected in this part of aquifer 2, it is considered that either the groundwater seeps into the permeable terrace gravel-bodies, which lie on limestone on the northern side of aquifer 2 and are thus in hydraulic continuity with the aquifer, and returns through them to the Alfios river further north, or that the groundwater percolates downwards to an aquifer developed further down and discharging further north at a lower elevation. The latter case is considered less probable.

The Panagia spring, situated approximately 200 m north of the northern part of aquifer 2 and issuing at an elevation of 331.2 m, together with the Opiste Panagia spring, situated approximately 400 m further north and emerging at an elevation of 330.65 m, are considered not to originate from aquifer 2. The water table/piezometric surface of aquifer 2 always lies at a lower elevation (326-329 m or often much lower) than that at which the springs issue. Furthermore, the hydrochemical investigations established that these springs are hydrogeologically associated with aquifer 1.

The hydraulic gradient from the Alfios river towards aquifer 2 was generally observed to be flatter at the end of the wet season than at the end of the dry season (Figs 12.50 and 12.56). This must be associated both with the reduced run-off of the Alfios river at the end of the dry season, when a small decline in the groundwater levels of aquifer 2 is sometimes noticed, and also with the availability of water for recharge.

The groundwater contour-maps reveal that, because of its relatively small size, aquifer 2, when pumping, has a much steeper hydraulic gradient from the Alfios river towards the aquifer than that which exists under natural conditions. When aquifer 2 is pumped, a very steep hydraulic gradient exists, directed from the Alfios river towards the pumping wells and the cone of depression formed affects the shape of the water table/piezometric surface of the whole aquifer.

A clear statement concerning the seasonal variations of the hydraulic gradient of aquifer 2 when it is pumping cannot be made, although it is probable that it is greater at the end of the dry season than at the end of the wet season, for the same reasons as referred to above but under natural conditions (ie when it is not being pumped).

Thus, as a general conclusion, it can be stated that aquifer 2, regardless of the season, is recharged from the Alfios river and that the hydraulic gradient from the Alfios river towards the aquifer is much greater when one or both of the production wells F6 and F7 are in operation.

A comparison of the groundwater contour-maps of aquifers 1 and 2 shows that aquifer 1 almost always has a higher groundwater level, the only exception being at the end of the dry period of 1977. Therefore, if hydraulic continuity exists between these two aquifers, it must be as aquifer 1 recharging aquifer 2. From the study of the hydraulic gradient in areas of possible hydraulic continuity (determined from the shape of the groundwater contour lines), it can be concluded that such a hydraulic continuity between these two aquifers is not present and that the only recharge sources for aquifer 2 are the Alfios river and the aquifer developed in the terrace gravel bodies of the Alfios river, adjacent to the northern side of the aquifer.

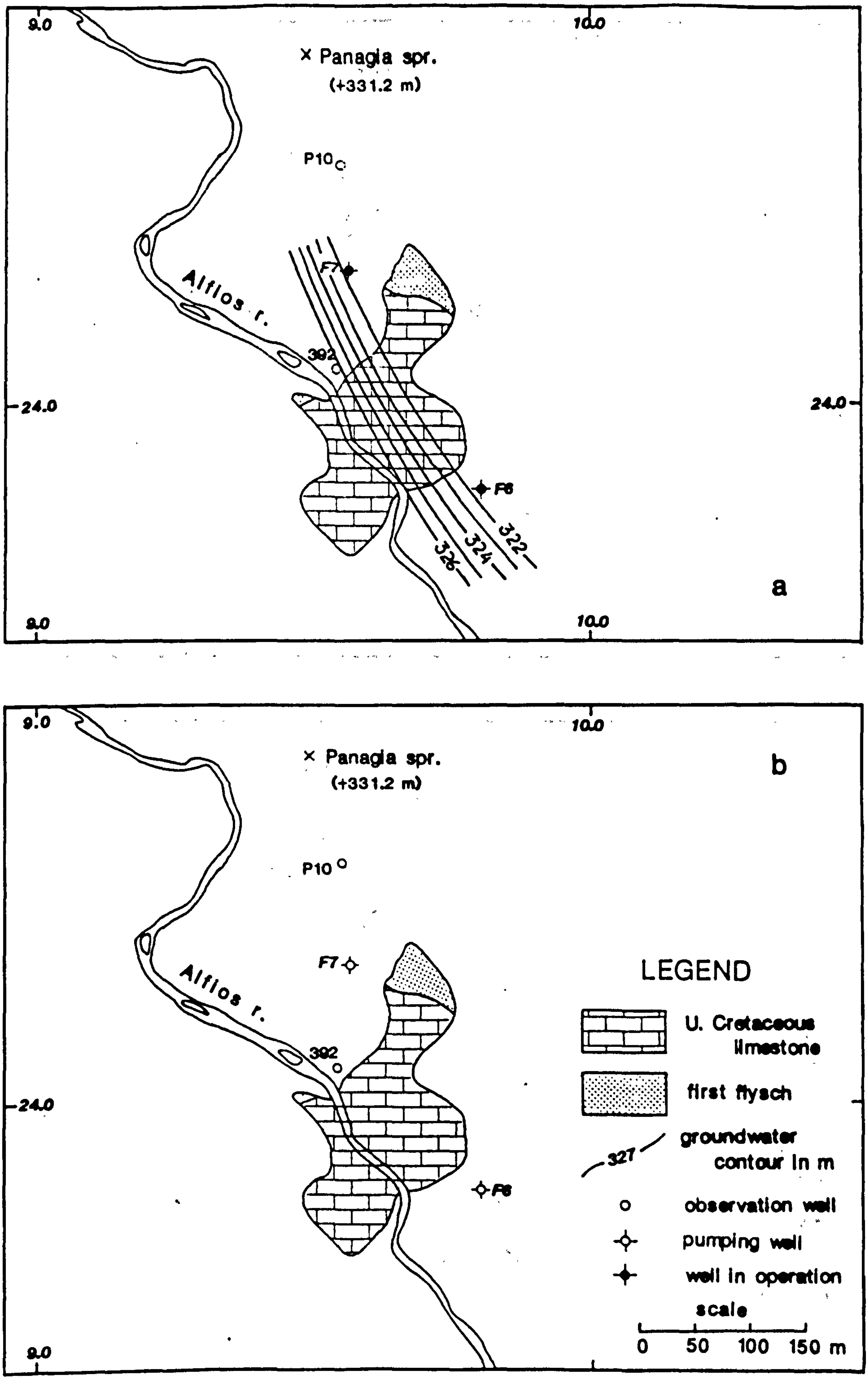


Fig 12.50 Map of the hydraulic head distribution in aquifer 2; groundwater levels recorded on 7 December 1975.

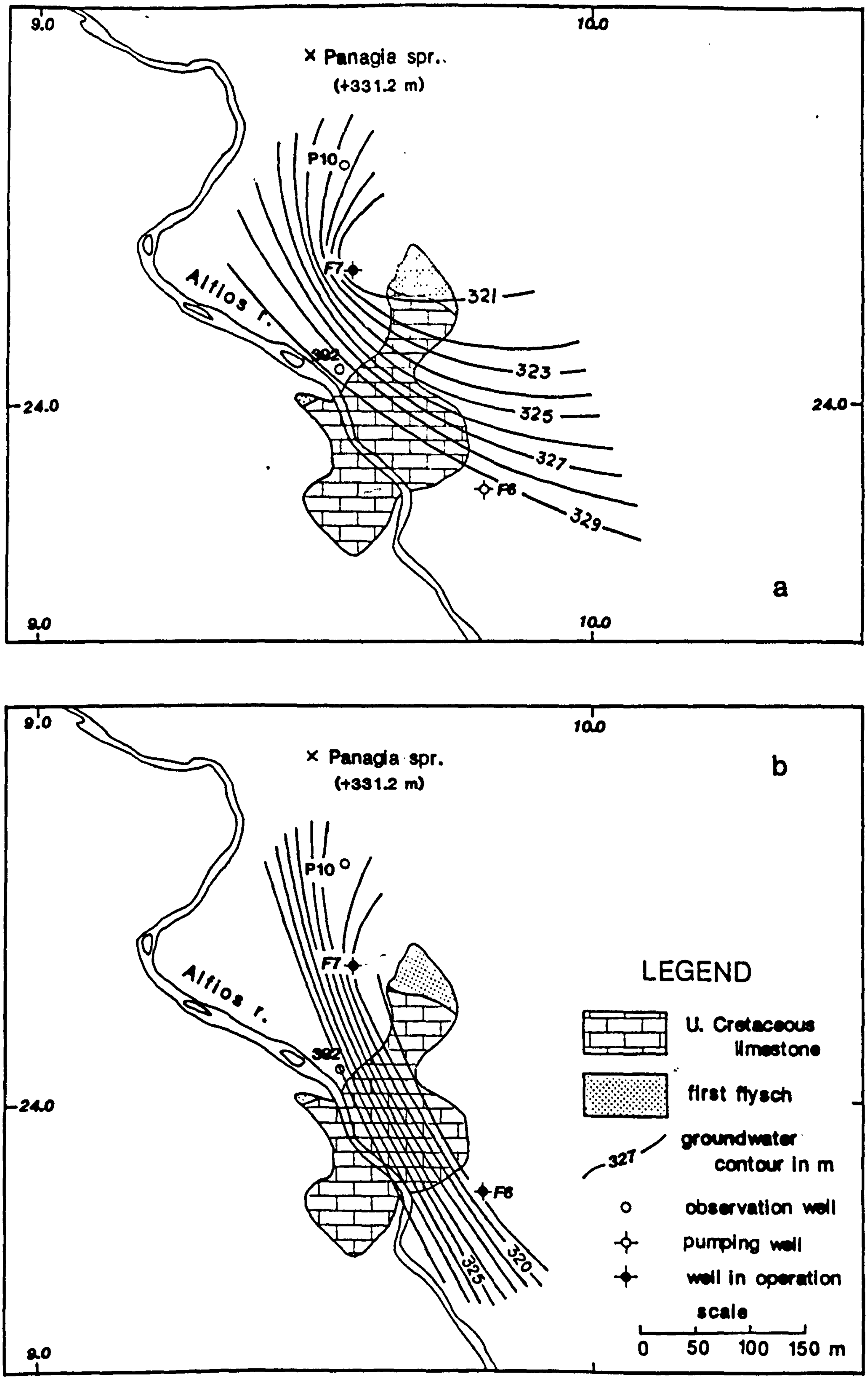


Fig 12.51 Map of the hydraulic head distribution in aquifer 2.
a) Groundwater levels recorded on 16 May 1976.
b) Groundwater levels recorded on 21 November 1976.

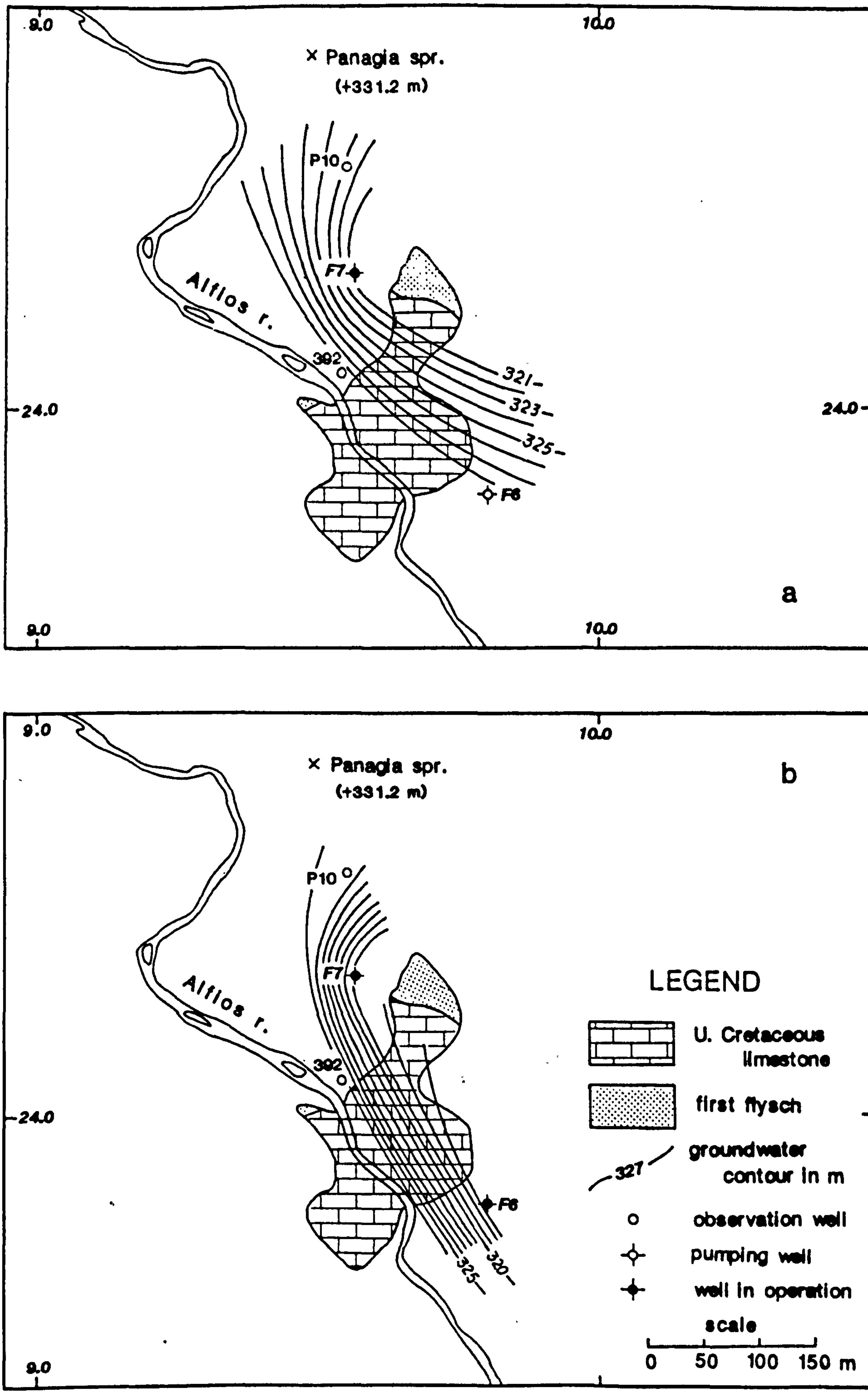
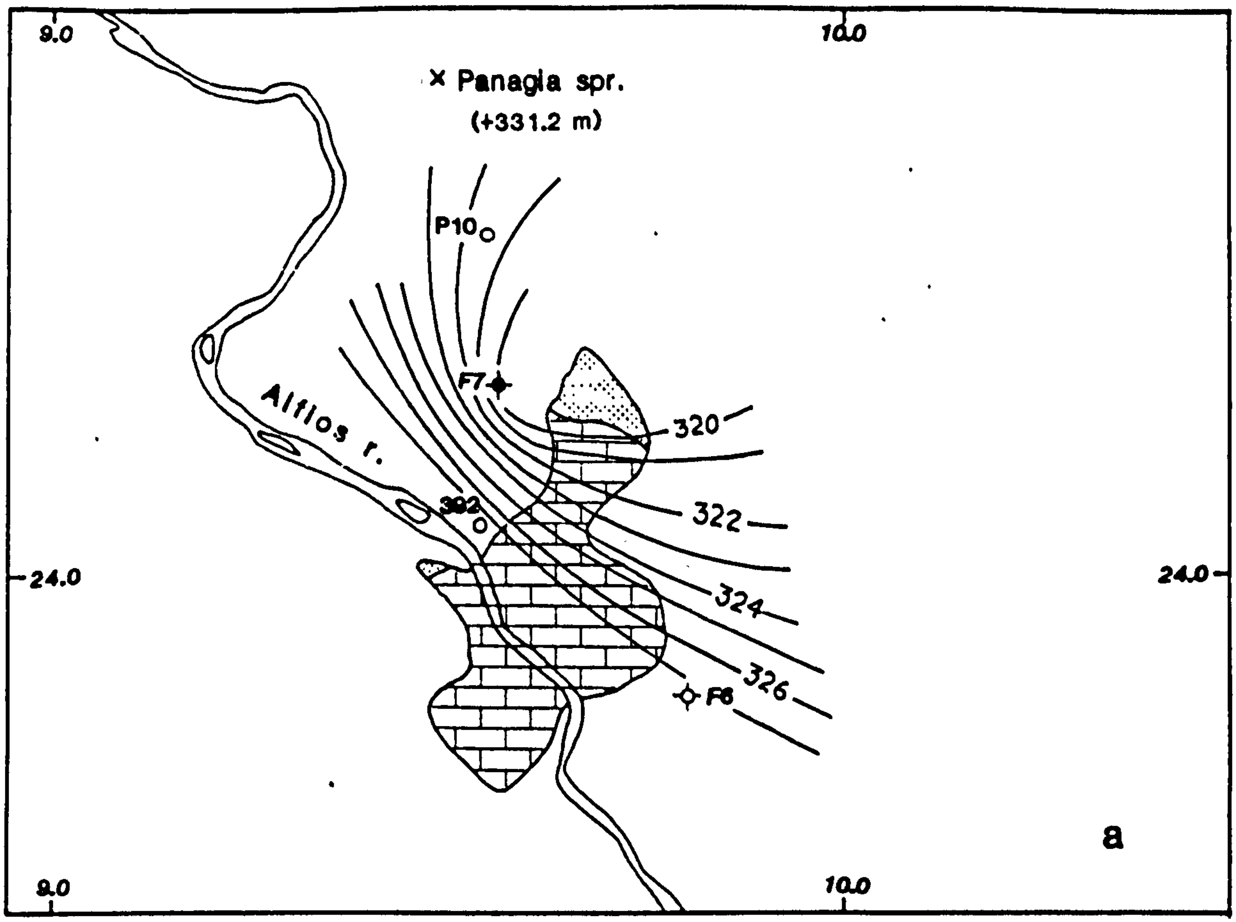


Fig 12.52 Map of the hydraulic head distribution in aquifer 2.
a) Groundwater levels recorded on 15 May 1977.
b) Groundwater levels recorded on 13 November 1977.



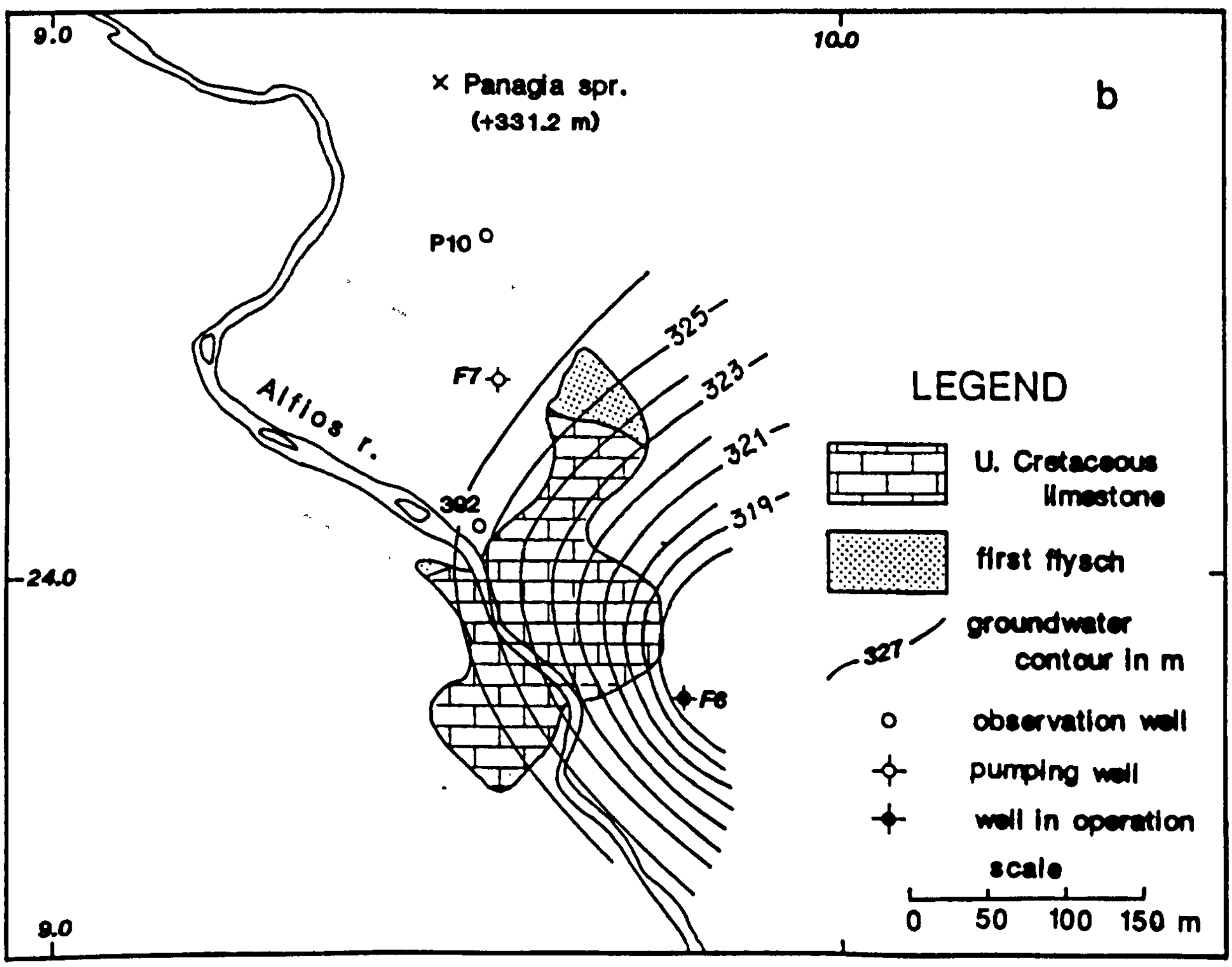
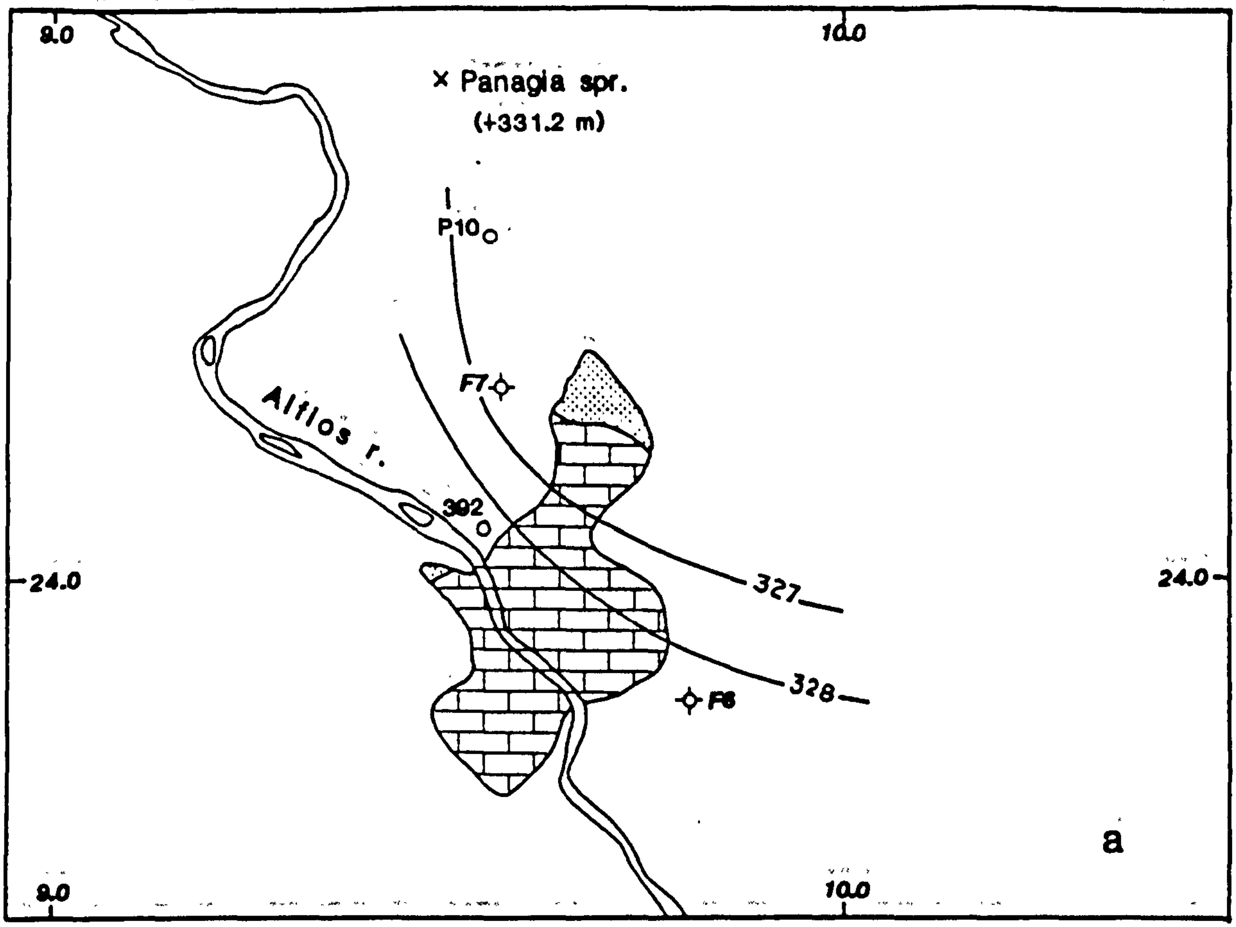


Fig 12.53 Map of the hydraulic head distribution in aquifer 2.
a) Groundwater levels recorded on 14 May 1978.
b) Groundwater levels recorded on 12 November 1978.



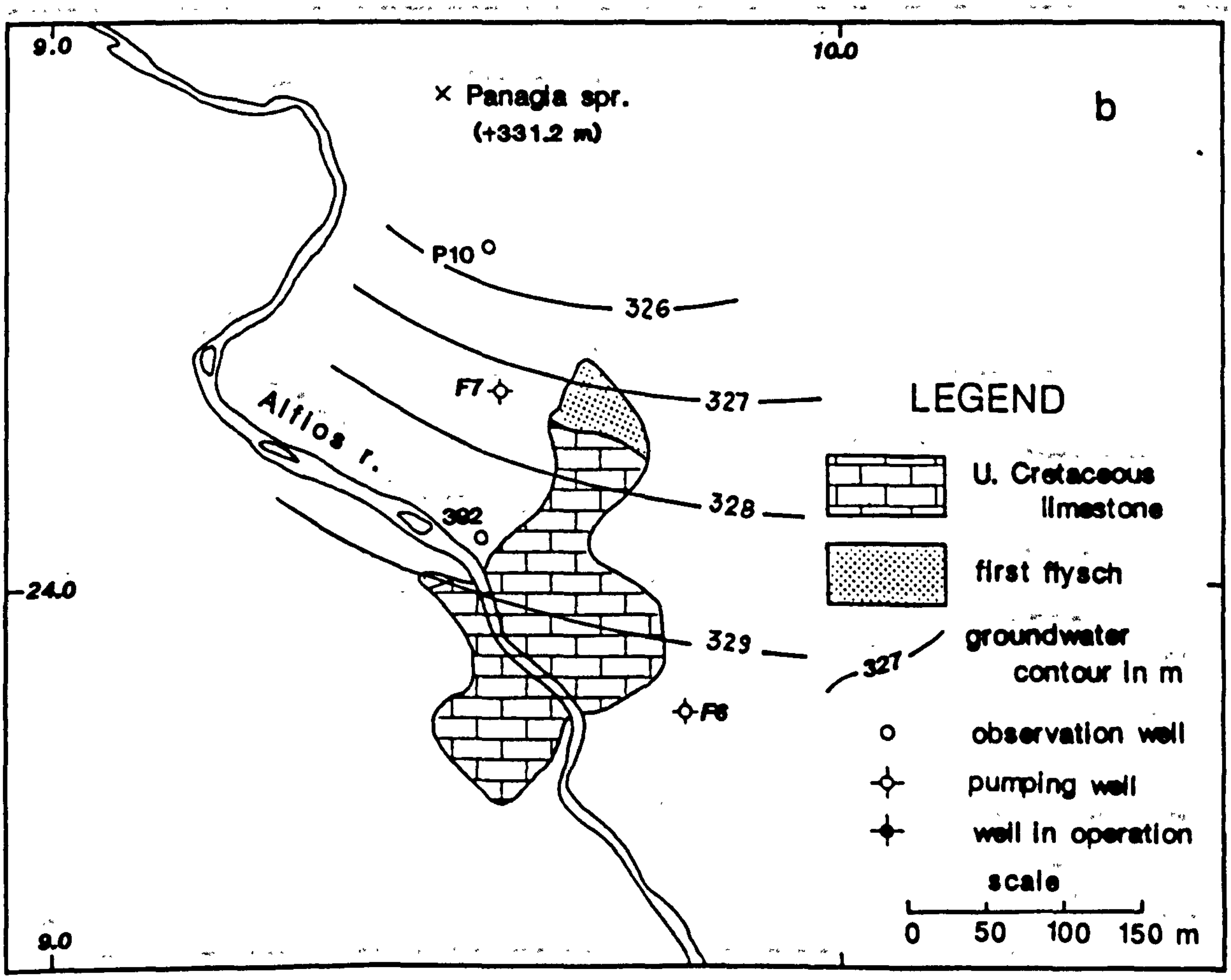
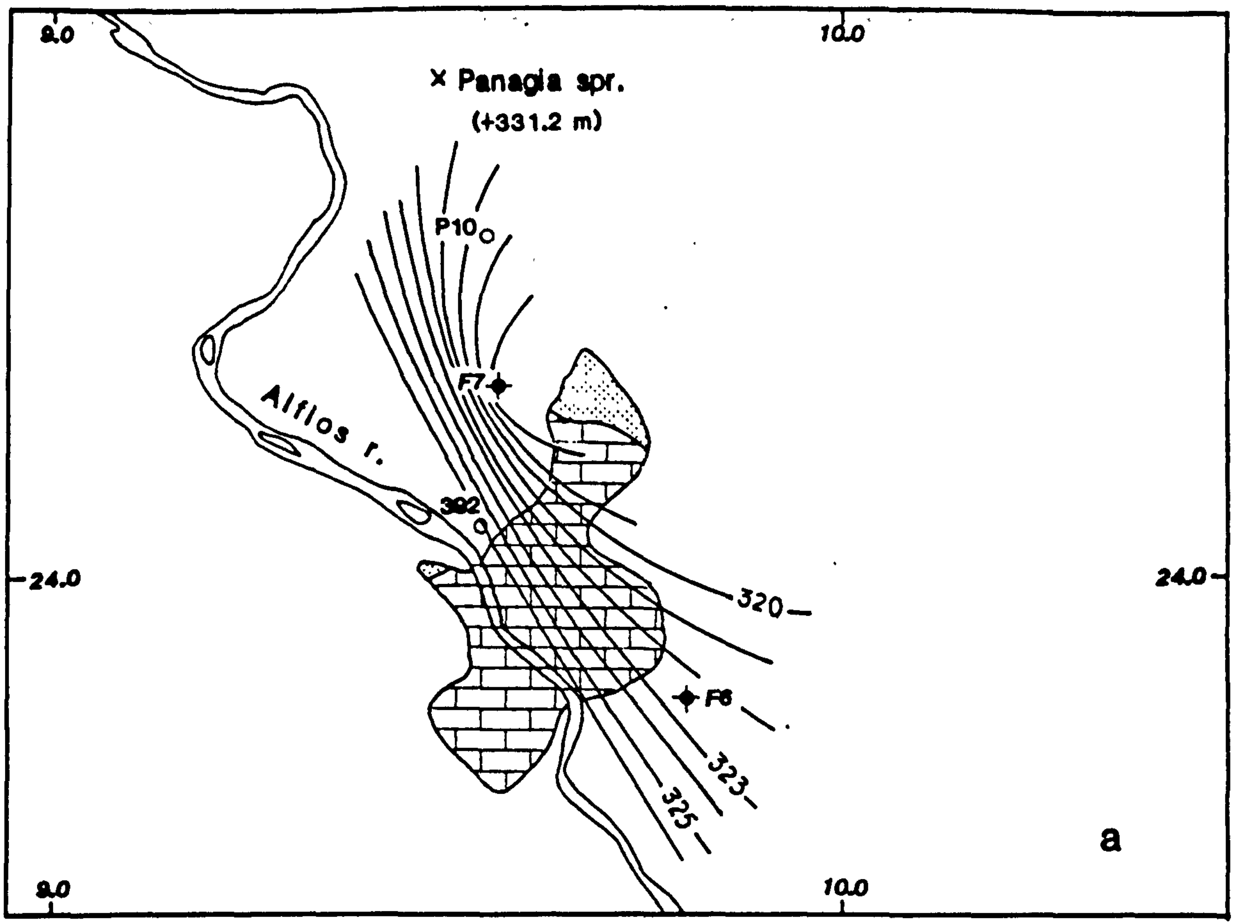


Fig 12.54 Map of the hydraulic head distribution in aquifer 2.
a) Groundwater levels recorded on 20 May 1979.
b) Groundwater levels recorded on 18November 1979.



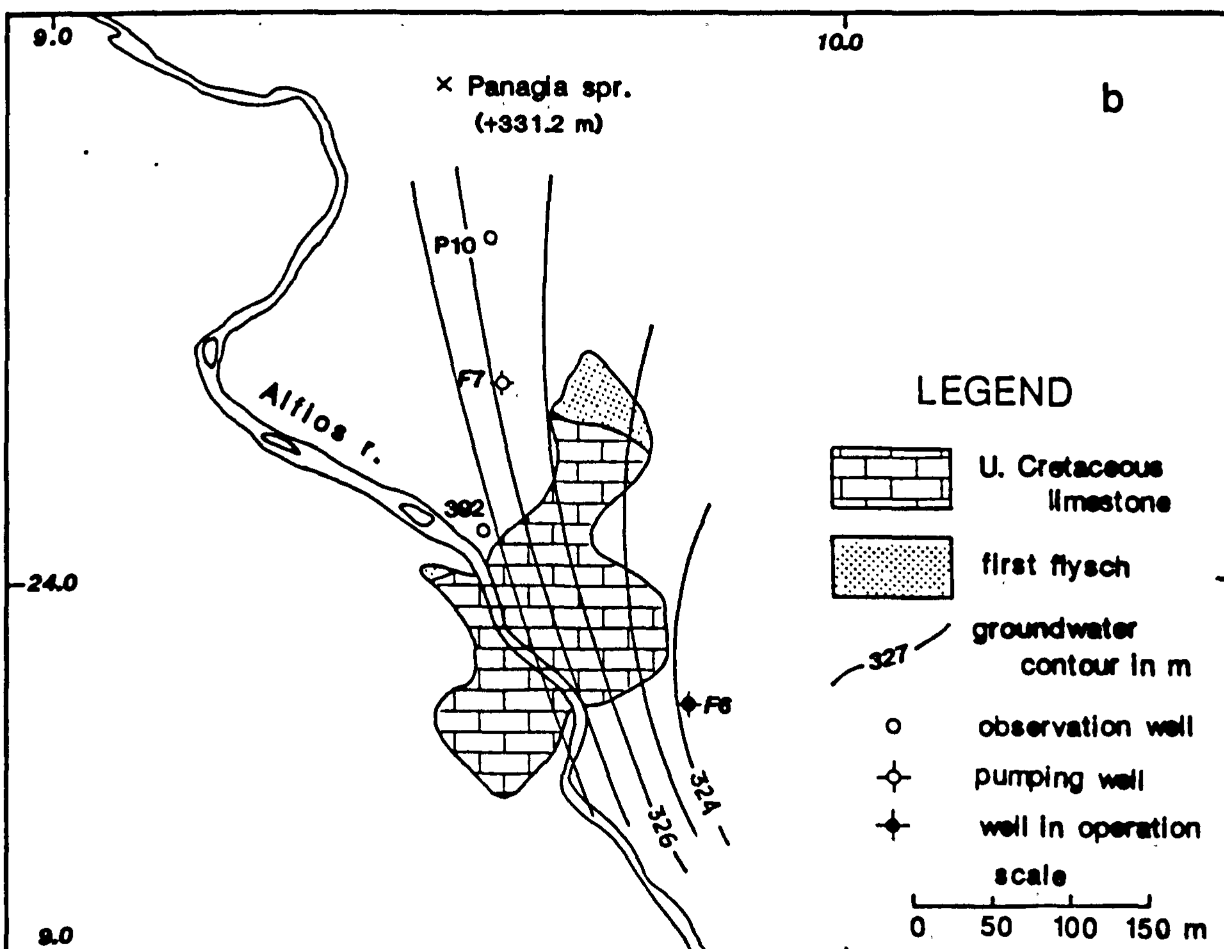


Fig 12.55 Map of the hydraulic head distribution in aquifer 2.
a) Groundwater levels recorded on 11 May 1980.
b) Groundwater levels recorded on 16 November 1980.

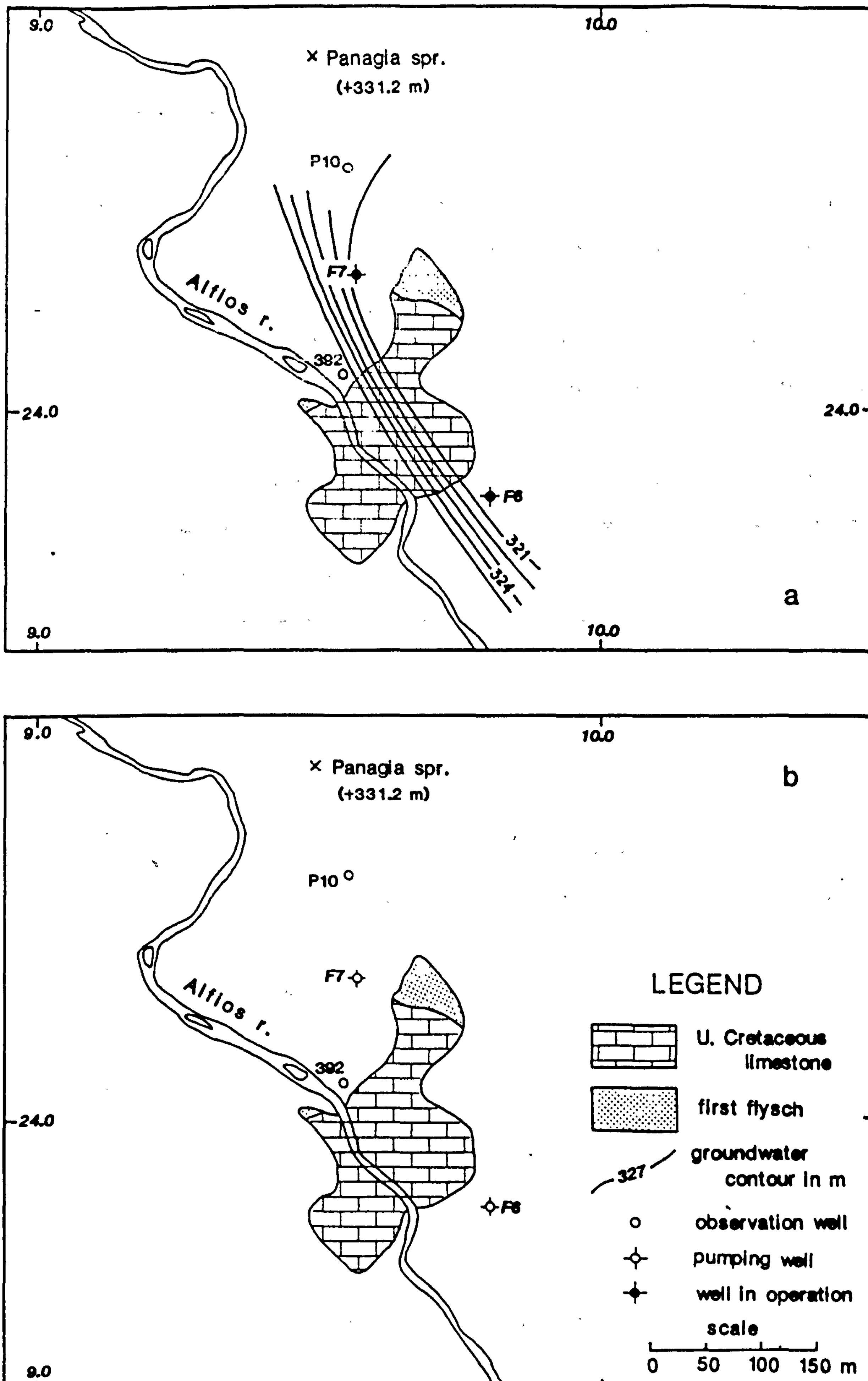


Fig 12.56 Map of the hydraulic head distribution in aquifer 2; groundwater levels recorded on 17 May 1981.

12.3 Aquifer No 3

12.3.1 Introduction

Aquifer 3 is also of small extent and takes the form of an elongated karstic aquifer along the western side of the future mine of the Kyparissia field and extending northwards beyond the field (Fig 11.8).

The limestone of this aquifer does not outcrop anywhere, being completely covered by the impermeable basin sediments of the Apiditsa stage and the Marathousa beds.

There are four water gauges in this aquifer, ie the wells F8/72, F10/72 and the observation wells P12 and 376. Wells F8/72 and F10/72 were constructed in 1972 to supply the power station with water but the main pumping tests proved them to be unproductive. Remarkably large drawdowns were recorded but only small discharges.

The study of the well hydrographs shows that aquifer 3 is in widespread hydraulic continuity with aquifer 2 in the area around production well F6. The reason for considering aquifer 3 as individual is that the wells F8/72 and F10/72 are not nearly as productive as wells F6 and F7 in aquifer 2 (see Section 12.1.5.3), suggesting a much lower permeability in aquifer 3.

The well hydrographs for the observation period (1975-81) do not show any significant seasonal or annual fluctuations, while the irregular fluctuations present in all these wells follow the drawdowns recorded in well F6 (situated in aquifer 2) when it is being pumped. Any small annual fluctuations, if present, exhibit the same pattern as those of aquifer 2.

The groundwater hydrographs of the wells F8/72, F10/72 and P12 are very similar and, in fact, almost identical to that of the production well F6 (Figs 12.57 and 12.58). A few measurements incompatible with those of other stations are distinguished in each well hydrograph. These were considered to be erroneous.

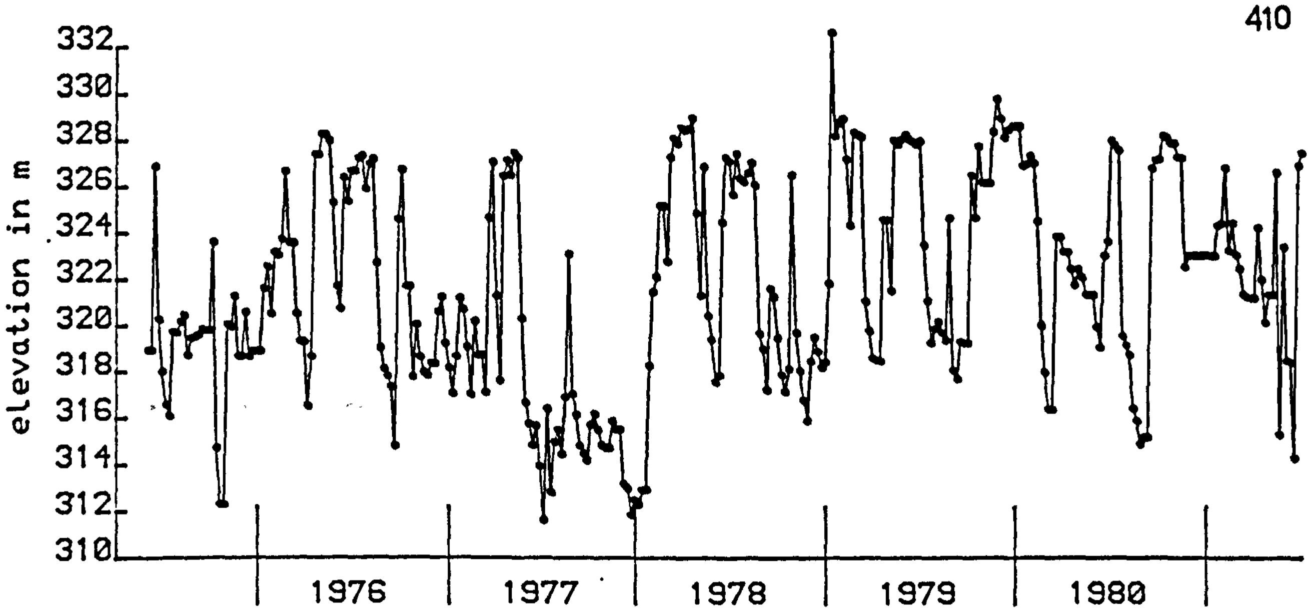


Fig 12.57 Hydrograph of the production well F6, sunk in aquifer 2.

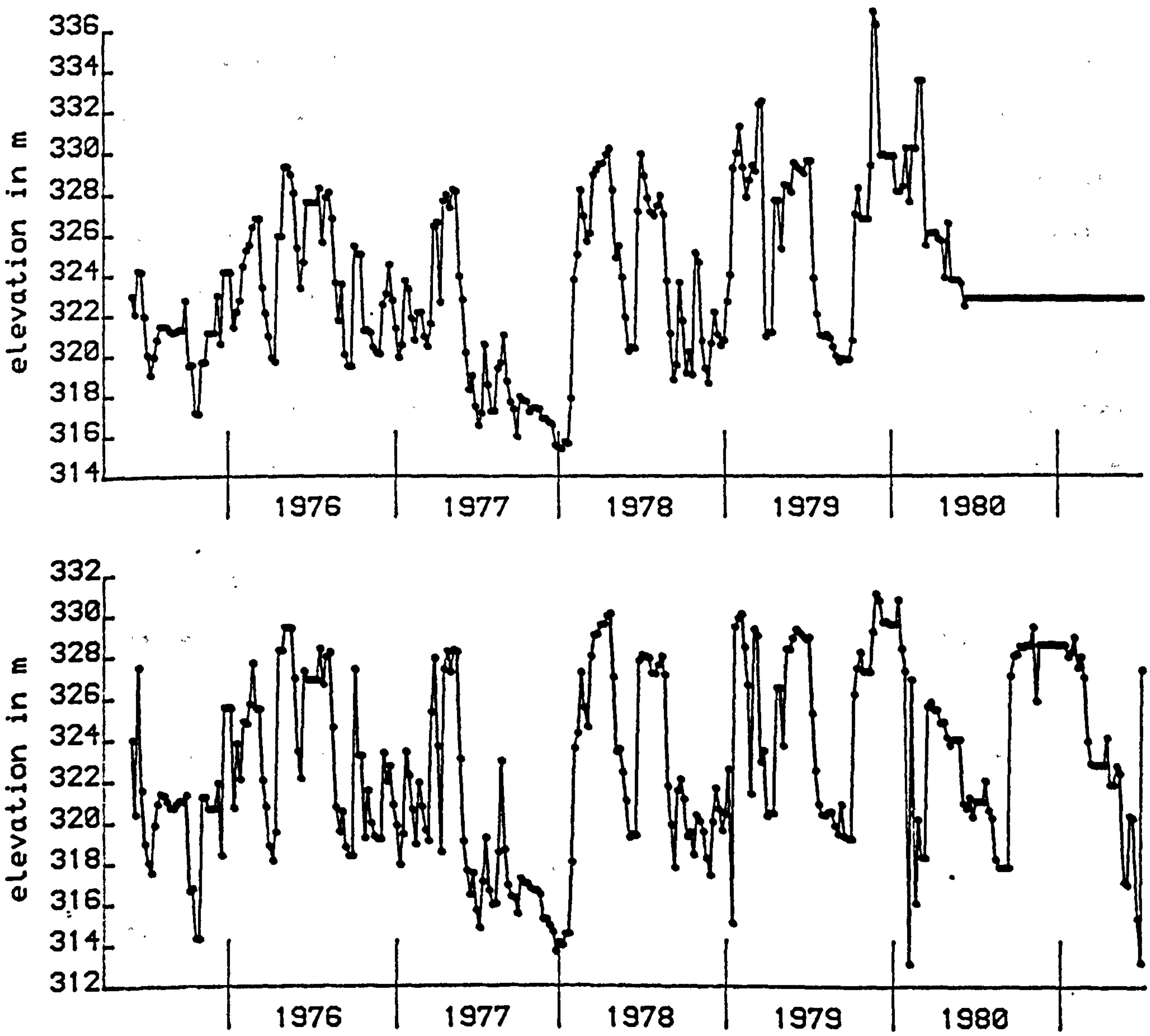


Fig 12.58 Hydrograph of wells: a) F8/72 and b) F10/72, sunk in aquifer 3.

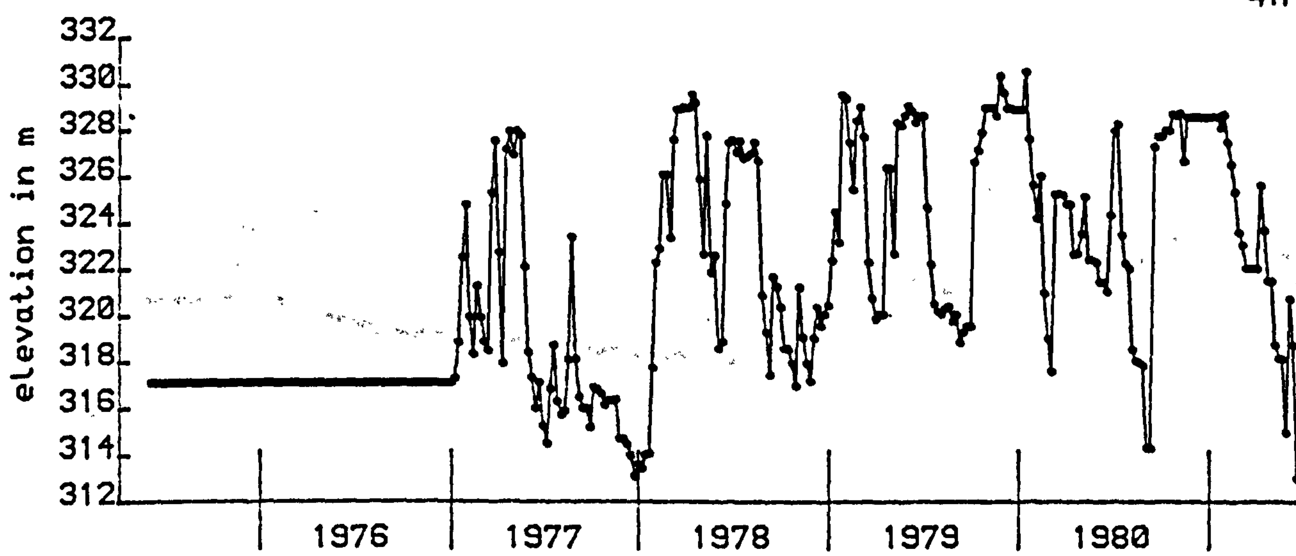


Fig 12.59 Hydrograph of well P12, sunk in aquifer 3.

The downwards fluctuations recorded in well F8/72 are some 1 to 2 m below those recorded in wells F10/72 and F6. The groundwater hydrograph of well P12 (Fig 12.59) is almost identical to that of well F10/72.

It is a striking fact that the drawdowns recorded in well F6 are closely similar, though reduced by 1 to 2 m, to those of well P12, which is situated 1,750 m away from the production well F6. This implies that an almost flat piezometric surface, extending as far as the observation well P12, is established when the well F6 is being pumped. This shows the limited extent of aquifers 2 and 3 towards this area where the observation well P12 is situated. Furthermore, the fact that the resulting hydraulic gradient in this direction is very small shows that recharge of aquifers 2 and 3 does not take place from this side.

The groundwater hydrograph (Fig 12.60) of the observation well 376 is a special case. This well was sunk into aquifer 3 and cased with a blind pipe down to the surface of the limestone.

During most of the observation period, well 376 must have been plugged at a certain depth above the limestone surface and the measurements taken should therefore have corresponded to the groundwater level of a shallow aquifer developed in the basin formations (see also

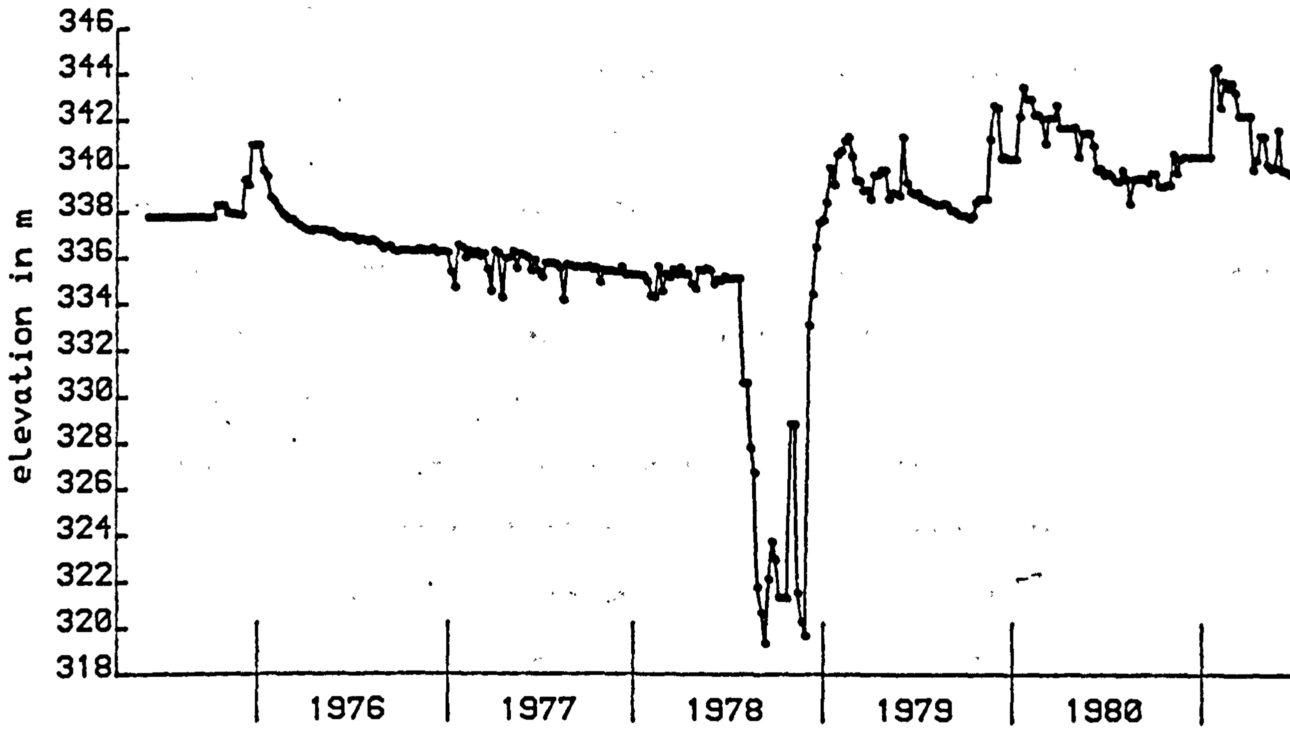


Fig 12.60 Hydrograph of well 376, sunk in aquifer 3.

Section 11.3). For a short period of approximately 20 weeks when it had been either artificially or naturally unplugged, it experienced the same fluctuations as the other observation wells of this aquifer.

Groundwater contour-maps were not drawn for aquifer 3 because of the restricted number of observation wells existing. Furthermore, the groundwater level of aquifer 3 does not show seasonal fluctuations and maps of the higher and lower groundwater level/piezometric surface could not, therefore, be drawn. The level of the groundwater recorded in the observation wells of aquifer 3 on the respective dates for which the maps of the lower and higher piezometric surface for aquifer 1 were drawn are noted on Figures 12.23 to 12.34 and Appendix III.

An almost flat piezometric surface, dipping gently towards well F6, exists in aquifer 3 when the production well F6 is pumping. From the evaluation of the data on the groundwater levels recorded in aquifer 3, it can be seen that a flat piezometric surface also exists when pumping does not take place in aquifer 2.

12.4 Aquifers 4, 5 and 6

Aquifer 4 is very small and occurs to the north-east of the village of Kyparissia. It is developed in a small limestone subcrop, totally covered by the basin sediments. Its groundwater is under confined conditions. Recharge and discharge of this aquifer must take place through the relatively permeable parts of the basin sediments (ie Apiditsa stage) in the form of seepage.

There is only one observation well, P13, drilled in this aquifer. The groundwater hydrograph of this well shows seasonal and also annual fluctuations (Fig 12.61). The seasonal fluctuations ranged between 2 and 5 m. The water table of aquifer 4 lies at an elevation of 335-343 m and is always higher than that of aquifer 1.

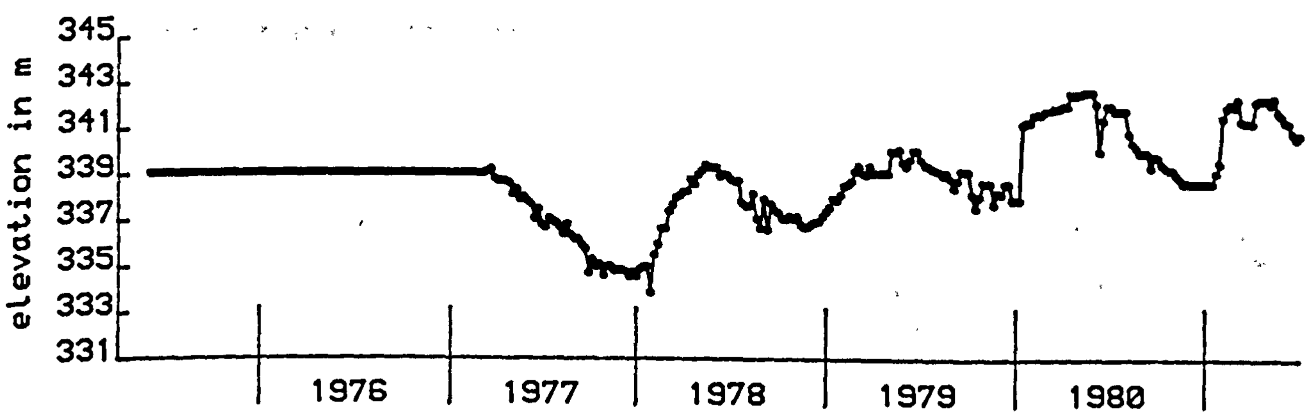


Fig 12.61 Hydrograph of well P13, sunk in aquifer 4.

Aquifer 5 is also small and is developed to the north of the village of Kyparissia. It also occurs under confined conditions.

There is only one observation well, P15, drilled in it. The seasonal fluctuations of the water table recorded in it ranged between 7 and 10 m (Fig 12.62). The water table lies at an elevation of 333-346 m and is always higher than that of aquifer 1.

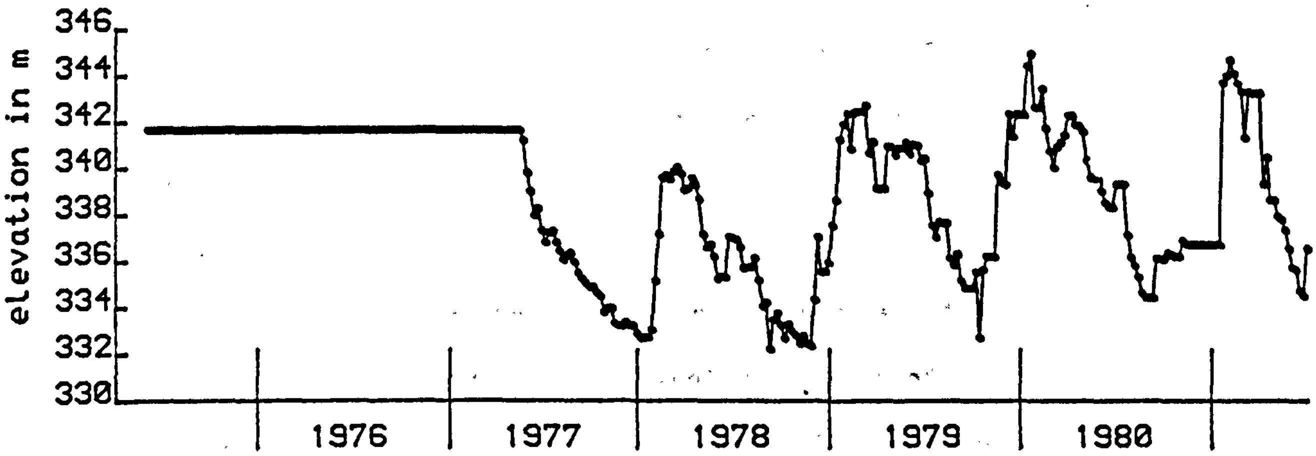


Fig 12.62 Hydrograph of well P15, sunk in aquifer 5.

Aquifer 6, of a relatively large size, is developed to the north of the villages of Kyparissia and Mavria (Fig 11.8). For most of its extent, it is confined by the basin sediments of the Apiditsa stage and only in two places, east and north of the village of Mavria, does it outcrop for small distances.

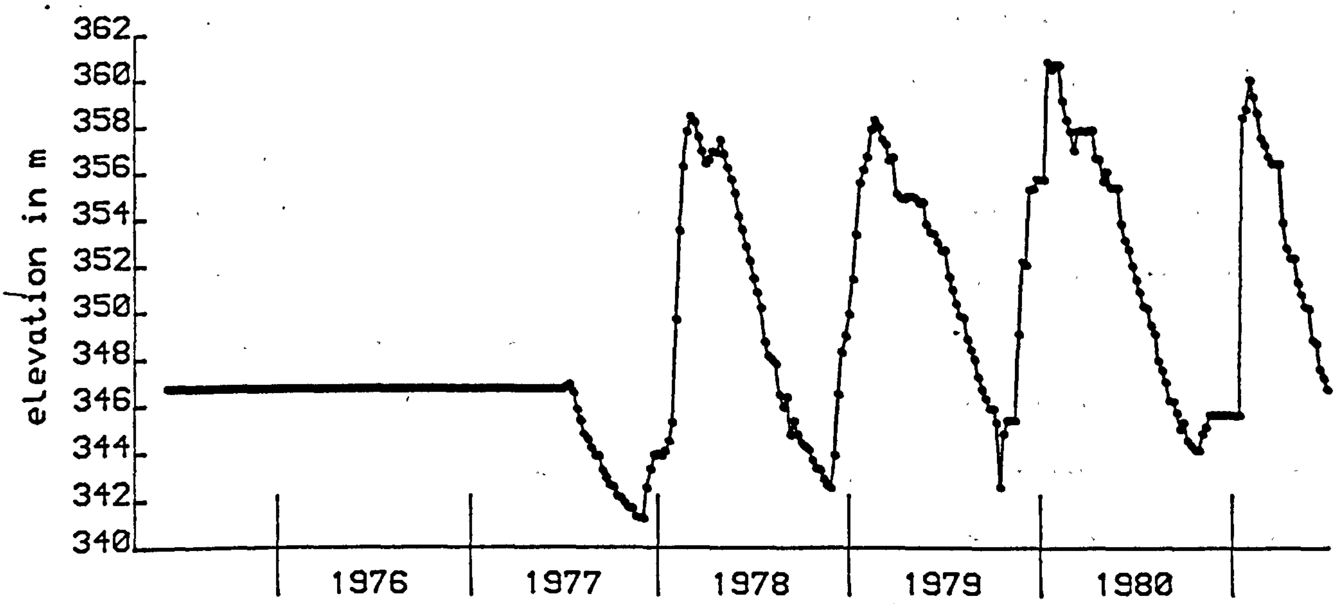


Fig 12.63 Hydrograph of well P14, sunk in aquifer 6.

Two observation wells, P14 and 383, are drilled in the aquifer. Only for well P14 were there adequate data for a hydrograph to be drawn. The groundwater hydrograph of this well shows large seasonal fluctuations of a range of 16 m and only small annual fluctuations (Fig 12.63).

Aquifer 6 has the highest water table level of the karstic aquifers developed in the vicinity of the Kyparissia field. It lies between 342 and 362 m. It has a small discharge through the Mavria spring, situated at an elevation of 340.75 m.

The fact that aquifer 3 occurs between aquifers 5 and 6, which always have a higher water table level than that of aquifer 1, indicates that no groundwater enters the main aquifer 1 from a westerly direction.

12.5 Conclusions

1) Aquifer 1 is the largest of the karstic aquifers developed in the Kyparissia area. Its western extent is well defined but its eastern boundary cannot be accurately determined as part of the groundwater from the Upper Cretaceous limestones outcropping on this side percolates down to a deeper aquifer system. Aquifer 1 is considered to be of limited eastward extent although its precise boundary could only be accurately determined by the sinking of boreholes further east.

2) For most of that part of its extent which occurs in the Kyparissia field, aquifer 1 is confined by the relatively impermeable unconsolidated basin sediments.

3) Recharge of aquifer 1 takes place mainly from the Kyparissia stream which crosses and enters it at an elevation of approximately 360 m and is influent to the aquifer during its entire period of flow. Aquifer 1 is in open hydraulic continuity with the Alfios river, which flows here at an elevation of 333 to 335 m, and with the aquifer developed in the terrace gravel-bodies.

4) Aquifer 1 discharges through the springs located around the Kyparissia bridge (eg that of Aghia Sotira), through the Panagia and

Opiste Panagia springs (as seen from the study of the hydrograph of well P9, situated next to the Panagia spring) and also directly into the Alfios.

5) The groundwater level in aquifer 1 exhibits only long term fluctuations, ie seasonal and annual. The lowest level recorded during the period of observation (1975-81) was 325-326 m (November 1977), while the highest was 339-340 m (May 1980). A rise of approximately 1 m per year on average was noticed during the observation period. It is related to a corresponding increase in the total annual precipitation over this period. The wells situated around the area where the Kyparissia stream percolates down to the aquifer show short term fluctuations and exhibit a greater upwards range of fluctuations than the other wells situated in aquifer 1.

6) Study of the pumping tests and of the well hydrographs of the production wells F1 to F5, F8 and F9 shows that the further away the well is situated from the Kyparissia bridge, the greater is the drawdown recorded when the well is pumped. This proves that the Alfios river is in hydraulic continuity with aquifer 1 in this area.

7) Values of transmissivity calculated for aquifer 1 in the area in which well P1 is sunk range from 26 to 170 m^2/day, while the storage coefficient is calculated at between 0.0001 and 0.02. These differences in the values calculated are not considered to be due to an anisotropy of aquifer 1 but, rather, to the presence of different boundary conditions within the extent of the aquifer.

8) Under natural conditions, no detectable, significant long or short term fluctuations are noticed in the groundwater level of aquifer 2 throughout its relatively small extent. The water table/piezometric surface of this aquifer lies at an elevation of between 325 and 329 m, slightly lower than the elevation at which the Alfios crosses

the aquifer (approximately 329-330 m). A high degree of hydraulic continuity between the Alfios river and aquifer 2 is also evident here. The drawdown recorded in the production wells F6 and F7 when they are being pumped averaged 8 to 10 m and is generally marginally smaller in well F6 which is situated closer to the Alfios.

9) According to the study of their hydrographs, the wells situated in aquifer 3 exhibit the same pattern of fluctuations in aquifer 2, thus showing aquifer 3 to be in open hydraulic continuity with aquifer 2 in the area around well F6. The only reason for considering aquifer 3 to be an individual, hydrologically isolated unit is that the wells F8/72 and F10/72 are not nearly as productive as wells F6 and F7 sunk in aquifer 2 and this suggests that aquifer 3 is of lower permeability.

10) Groundwater of completely different hydraulic heads is seen in the smaller aquifers 4, 5 and 6 developed on the western side of the Kyparissia field and the hydraulic heads present here are also different from those in aquifers 1, 2 and 3. The groundwater level in aquifers 4, 5 and 6 shows only long term fluctuations. The Mavria spring is hydrogeologically associated with aquifer 6.

PART IV HYDROCHEMISTRY

CHAPTER 13: INTRODUCTION

Chemical and hydrochemical investigations of groundwater, whether from the karstic or other aquifers, can reveal much concerning the origins of the water in the aquifer, and can be used to detect the mixing of water of different compositions and to identify chemical processes occurring as groundwater moves through the subsurface strata.

The objectives of this study are (1) to establish a relationship between the chemical composition and hydrology of the groundwater in the Kyparissia field; (2) to establish a probable mechanism by which the groundwaters may have acquired their chemical character; (3) to elucidate the origin of the groundwater of the karstic aquifer developed below the Kyparissia field; and (4) to clarify any possible relationship between the water in the aquifers and the surface water from the Alfios river or the water from the karstic springs.

Twenty-two locations were chosen and it was suggested that samples be taken and analysed at monthly intervals throughout 1984 in order that a complete study could be undertaken.

Unfortunately, it was only possible to take and analyse four sets of samples from 14 locations (Fig 13.1), these samples being taken in February, August, September and October. Of the analyses carried out, one was done by the author and the remaining three by the IGME Laboratories.

The samples were analysed to determine the concentrations of the major chemical constituents (calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulphate and nitrate) by standard methods.

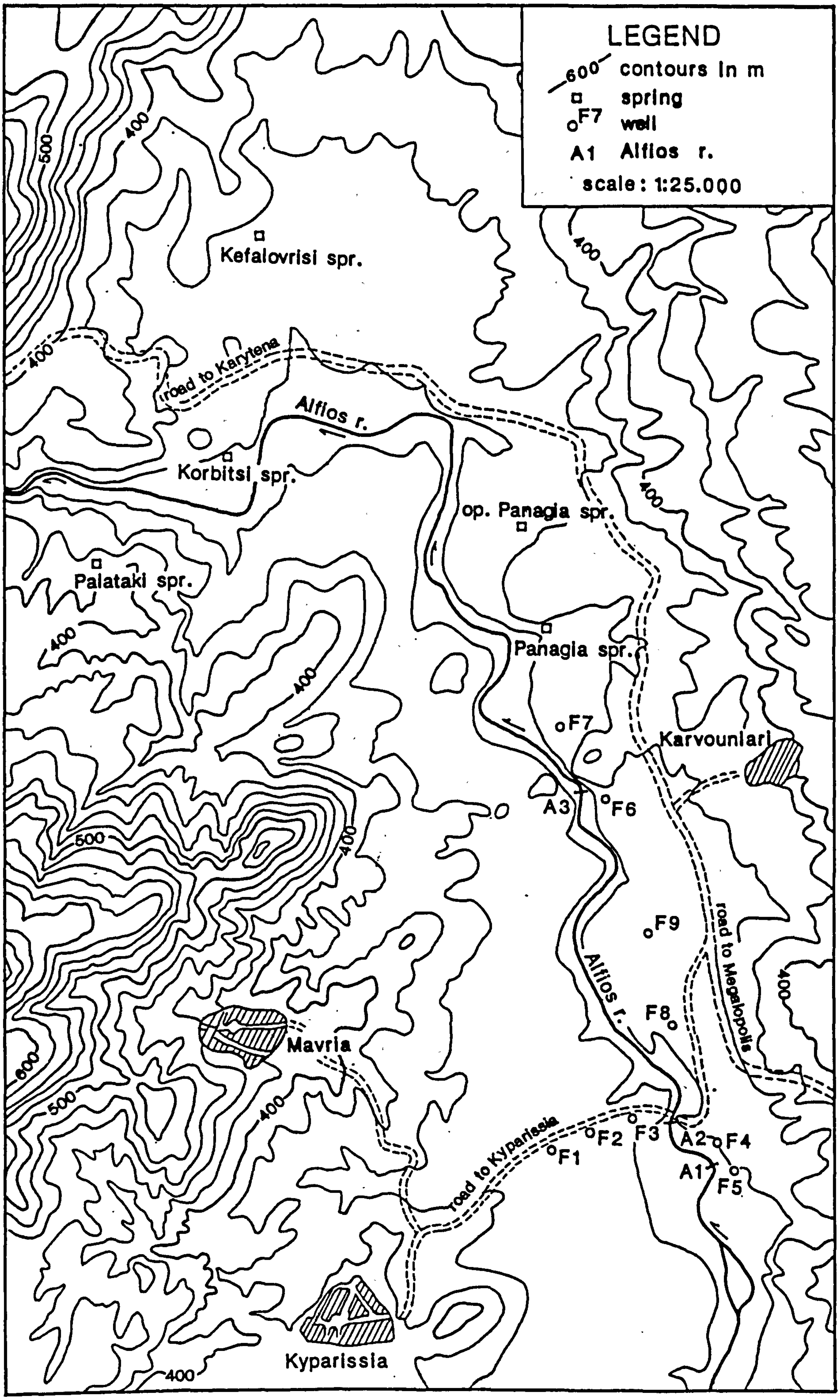


Fig 13.1 Map showing the locations from which the water samples were obtained.

A total of 95 analyses were used in this study and the results are given in Appendix IV(*). Chemical data included in previous studies (Gold Report 1963, Hydroerevna Research Company Report, 1975) were only used for comparing temporal variations.

Chemical analyses of natural water may be inadequate due to a margin of human error and to sample ageing. All analyses were checked for equivalence between ionic concentrations of anions and cations. In a correct and complete analysis, the combined (equivalent) weight of the cations should agree with the combined (equivalent) weight of anions to some acceptable tolerance (5%) (Summers 1972, Zaropozec 1972).

The total dissolved solids (TDS) which can be determined directly are equivalent to the weight of the residue left after evaporation, the sample having been heated and dried for an hour at 180°C, or less commonly, at 110°C. This dried residue gives a rough estimation of the total dissolved solids, as gases are driven off, bicarbonate is converted to carbonate and sulphate is converted to gypsum, which contains water as part of its structure (Hem, 1970). However, total determined ions (TDI), obtained by the summation of the concentrations of the individual ions, are used in this study. According to Summers (1972), TDS and TDI should not differ by more than 10%.

Unfortunately, no pH or electrical conductivity (EC) field readings of the samples were taken. The temperature of the water in the springs was measured consistently, while that of the water of the Alfios river or in the boreholes was not measured.

(*) The chemical analyses are reported in equivalent parts per million epm (= parts per million/equivalent weights)

Usually, analyses of the samples were done one to two weeks after collecting. Water quality properties, such as pH, alkalinity (as bicarbonate) and EC are time dependent and, generally, field determinations of these variables are higher than those measured in the laboratory (Roberson et al. 1963), as water ageing leads to a slight reduction in the ionic concentrations (Summers 1972).

Graphical and numerical interpretations are used to aid study, classification, correlation and presentation of the water-quality data. There are a considerable number of different methods which can be applied (see Zaporozec 1972 for details).

In this study, the methods chosen are the commonly utilised method of Piper trilinear diagrams (1944), vertical bars (Collins 1923), Stiff diagrams (1951) and a few other numerical techniques (eg ratios).

By using Piper trilinear diagrams, the relative concentrations of the main ions present in an area can be identified. Collins diagrams are an effective way of presenting water composition, while Stiff diagrams are a relatively distinct method of demonstrating changes in the chemical composition of the water. Mathematical ratios (eg Ca/Mg in the case of carbonate aquifers) are one of the best ways of showing correlations and making comparisons between various water types.

The water types present in the area are described with reference to the chemical symbols of the major cations and anions, arranged in order of decreasing abundance, calculated as a percentage of the total in equivalent parts per million (epm). Ions present in amounts less than 10% of the total are excluded from the notation (Khan et al. 1972, Back 1961). Samples with the composition Ca^{++} 78%, Mg^{++} 17%, Na^{+} 5%, HCO_3^{--} 77%, SO_4^{--} 14%, Cl^{-} 7%, NO_3^{-} 2% will here be labelled, according to the above notation, as $Ca/Mg:HCO_3/SO_4$ type water.

After the physical and chemical parameters and the major ion hydrochemistry of the water had been determined and their contribution to the three sources of water occurring in the area (ie springs, karstic aquifers, river) had been studied and fully discussed, the chemical composition of each water type was extensively studied, correlations were established and the findings interpreted.

In the last part of this section, using the correlations already detected, a probable origin of the main aquifer water is identified and a possible relationship between the karstic groundwater and the Alfios river water established.

13.1 Physical and chemical parameters

Physical parameters

Temperature, pH and electrical conductivity (EC) are the main physical parameters of the water.

The temperature of the water has a very considerable influence on the solubility of the minerals, chemical compounds and gases. Changes in the water temperature will, therefore, affect the degree of saturation and could change an aggressive water into a saturated one or vice versa, possibly with some solution or precipitation of minerals taking place. Spring water temperature was notably consistent, ranging between 12° and 14°C, depending on the season of the year. No data are available for the aquifer water, while river water temperature is thought to vary significantly following the daily and seasonal variations in air temperature.

The pH value of the water indicates its acidity. This acidity may, in fact, be considered as mainly due to the carbonic acid in solution, so the lower the pH, the more likley the water is to be aggressive. The pH is very sensitive to changes in the partial pressure of the carbon dioxide and changes in CO_2 content therefore influence the pH of the water. In some cases, where Ca^{++} is the predominant cation, the limited solubility of the calcium carbonate tends to minimise the presence of carbonate ions in solution and this results in the pH being kept below 8.2. pH values of 9 or more are only found in relatively soft sodium bicarbonate waters.

Roberson et al. (1963) reported that there are often appreciable differences between laboratory and field determinations of pH. Generally, field determinations of pH and alkalinity are higher than those made in laboratories. These differences range from 0.0 to 2.8 pH units with an average of 0.3 units, the standard deviation being 0.5 pH units.

Hem (1961) also referred to this, stating that an average difference of about 0.3 pH units was revealed, experimentally, between field and laboratory pH determinations.

Field determinations are more representative of the water in its natural environment than are laboratory determinations and should, therefore, be used in thermodynamic calculations, such as saturation indices.

Smith (1965) reported that pH values measured in samples a few hundred metres downstream from the rising pool of a spring were higher by as much as 0.5 pH units than in samples taken from the spring itself.

Greater differences in pH, alkalinity and EC determinations are generally observed in samples with a low pH value of 4.8 to 7.0 due to the precipation of iron during the storage time and also in waters collected in areas where little or no calcium carbonate is present in the natural aquifers (Roberson et al. 1963).

The pH values of the water are an indication of the degree of saturation with calcium, in respect of the available carbon dioxide. High pH values (more than 7) are associated with undersaturated and aggressive waters.

Aquifer and spring water pH was always greater than 7, with an average value of 7.6, as is to be expected in a carbonate system where the bicarbonate ion (HCO_3^-) is the predominant ion contributing to alkalinity. The Alfios river showed a slightly higher pH mean value of 7.8, due mainly to the presence of carbon dioxide in solution. Generally, higher pH values were measured during the colder season of the year (4 February).

Table 13.1 gives the mean and the minimum and maximum pH values measured during the present study in the water samples obtained from the various water-sources.

	Alfios River	Aquifer 1 Subzone A	Aquifer 1 Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
pH(1)	7.50-8.40	7.40-8.00	7.60-7.90	7.30-7.80	7.30-7.70	7.40-7.50	7.40-7.80
(2)	7.80	7.70	7.70	7.60	7.60	7.40	7.60

Table 13.1 pH values in the various water types (1) min-max values
(2) mean value

Specific electrical conductivity of an electrolyte is the reciprocal of the specific resistance of 1 cm^3 of solution at 25°C and is expressed in mhos. EC varies directly with temperature. The EC increases 0.2% for each increase in temperature of 1°C (Hem, 1970).

For most natural water of mixed type, the specific conductivity in mhos, multiplied by a factor of 0.65-1.0, provides an approximation of the residue on evaporation (TDS) in mgr/l and is, therefore, an indirect measurement of the total ionic concentration. This relationship is not totally reliable, for the conductivity is dependent on the type, as well as on the total quantity, of the ions in solution (Brown et al. 1972).

Table 13.2 gives the mean and min-max values of EC (in mhos) and total determined ions (TDI) (in meq/l) measured.

	Alfios	Aquifer 1 Subzone A	Aquifer 1 Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
EC mhos	410-770 560	430-550 490	320-430 385	480-610 550	340-490 430	440-500 470	285-430 370
TDI meq/l	9.7-15.6 (*) 11.72 (**)	9.8-11.6 10.58	8.0.8.5 8.25	11.2-12.1 11.27	9.3-9.9 9.61	9.9-10.6 10.28	7.6-8.4 8.01

Table 13.2 Min-max(*) and mean(**) values of EC and TDI measured in the various water-sources.

EC determinations were made under varying laboratory temperatures (see Appendix IV) which were also different from field temperatures and accurate comparisons cannot, therefore, be made.

From Table 13.2, however, it can be seen that there is a high degree of correspondence between mean EC and mean TDI for all water types, the conversion factor being approximately 45, ie TDI (meq/l) x 45 = EC (mhos). The Alfios river and aquifer 2 have higher values in both parameters than the other water sources, although low values of EC and TDI were generally determined.

Seasonal responses, especially in the Alfios river, in the total ionic concentration determination and, therefore, in the EC measured, were observed, with the higher values noted during the warm season, due to the fact that the solubility of the various minerals, chemical compounds and gases is dependent on the temperature of the water.

Chemical parameters

Hardness

Hardness results from the presence of divalent metallic cations but, as all the other cations except Ca and Mg usually occur only in trace amounts, hardness is considered to be the sum of only the Ca and Mg ions. Hardness (Ht) is expressed as the equivalent of calcium carbonate:

$$Ht = Ca \frac{CaCO3}{Ca} + Mg \frac{CaCO3}{Mg} \text{ or } Ht = 25\,Ca + 41\,Mg$$

Water with hardness up to 75 mgr/l (as $CaCO_3$) is defined as soft water, with values of 75-150 mgr/l as moderately hard and with values of 150-300 mgr/l as hard water (Todd 1980). All the water samples analysed during the present study fall into the hard category, due mainly to the high bicarbonate content in solution.

Total hardness is subdivided into carbonate and non-carbonate hardness, depending on the form in which the Ca and Mg ions are present.

The terms carbonate or temporary hardness are used to denote hardness related to the carbonates (Ca and Mg) and bicarbonates present in the water. Non-carbonate or permanent hardness, the remaining hardness going to make up the total, is caused mainly by calcium and magnesium sulphates and chlorides in solution.

It is to be expected that, in springs with seasonal fluctuations, minima in $CaCO_3$ concentration and in hardness values will be exhibited in the water chemistry at times of high recharge.

The temporal variations in hardness are a better index of the aquifer type than is hardness itself. These variations are related to the flow-pattern in the carbonate aquifer. Variations in the diffuse-feeder system aquifers tend to be small, as they show a more constant hardness while, in conduit-feeder system aquifers, the variations are greater (Shuster and White 1971).

Terran (1972) related the variations in hardness to the flow-through time of the groundwater. In the case of rapid passage of water through open conduits, there is comparatively little contact between the moving water and the bedrock, resulting in high variations in hardness. By contrast, in the diffuse systems, the slower rate of flow of groundwater is associated with a lower degree of variation in hardness.

Table 13.3 gives the total hardness and its temporary and permanent proportions for each water-type (in mgr/l as $CaCO_3$).

Hardness	Alfios River	Aquifer 1 Subzone A	Aquifer 1 Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
Total	218-351 (*) 268 (**)	232-275 252	190-202 198	264-278 272	224-232 230	240-254 248	182-202 190
Permanent	32-193 100	14-33 21	4-19 15	42-63 54	3-17 12	4-10 8	2-11 7
Temporary	123-203 168	217-244 231	175-189 184	209-236 218	207-229 218	230-250 240	173-194 183

Table 13.3 Min-max(*) and mean(**) values of hardness (as $CaCO_3$ mgr/l) in the various water bodies.

All water-types in question here have a high total hardness but they can be differentiated according to the degree of carbonate and non-carbonate hardness proportionately contributing to the total hardness. The springs, together with aquifer 1, have a very low permanent hardness and a high temporary one as a result of the high calcium bicarbonate content in solution. In contrast, aquifer 2, and especially the Alfios river, have a high permanent-hardness and a lower temporary one, resulting from the high sulphate content in solution in these water bodies.

Seasonal fluctuations in hardness were not distinguished in springs, even in the Kefalovrisi spring which has a winter-summer discharge ratio of 20:1. The small variations in the determined values could be indicative of the water-flow pattern. Otherwise, it must be concluded that these springs are fed from a diffuse-system aquifer.

The Alfios river exhibits seasonal variations in hardness and especially in its permanent portion with seasonal variations in the sulphate content also being great. This is mainly due to the different total run-off volume of the river during the year and to the different rate in contribution of the base-flow and direct run-off components, these having water of different chemical composition, to its flow during each season of the year. It is also affected by temperature changes.

The stability in hardness of the aquifer water will be discussed later.

Calcite saturation index

The saturation index of a sample, in respect of a mineral, which determines whether or not the water is in equilibrium with that particular mineral, reflects the degree of solution of that mineral.

In water taken from a limestone aquifer, given the abundance of calcite, the degree of saturation of the water with calcite depends on the resistance time and, therefore, saturation indices can be very useful for various studies, eg to define recharge areas. The degree of saturation should be lowest in recharge areas and should increase as water moves through the aquifer.

The calculation of the saturation index is quite complicated, requiring a lot of mathematical procedures (Burdon and Papakis 1963, Langmuir 1971, Shuster and White 1971).

The calculation of the saturation index of the calcite requires two constants for a given analysis of the water. These are:

(1) the equilibrium constant of the calcite (K_{cal}), and

(2) the calculated ion activity product (K_{iap}) of the dissolved ions Ca^{++} and HCO_3^-.

The equilibrium constant for calcite (K_{cal}), which is the theoretical constant for calcite at saturation point, can be obtained from physical tables ($K_{cal} = 9.7 \times 4.84 \times 10^{-11}$), as $CaCo_3$ goes into solution as bicarbonate (constants for reactions at 25°C).

The ion activity product (K_{iap}) is calculated using the equation

$K_{iap} = \dfrac{\alpha\ Ca^{++} \times KHCO3 \times \alpha\ HCO_3^-}{\alpha H^+}$, where $KHCO_3^- = 4.84 \times 10^{-11}$ (the equilibrium constant for bicarbonate), α = the ion activity of the various ions, which can be calculated, but can be determined more simply from a monograph and set of graphs provided by Hem (1961), and αH^+ = pH.

The saturation index of the calcite (SIC) can be expressed in two ways:

either (a) as a percentage: $SIC = \dfrac{K_{iap}}{K_{cal}} \times 100$

or (b) as a logarithm: $SIC = \log \dfrac{K_{iap}}{K_{cal}}$

Values of SIC less than 100 or 0 in (a) or (b) respectively indicate undersaturation and SIC greater than 100 or 0 respectively correspond to oversaturation.

The computation of the SIC for $CaCO_3$ in solution is inversely proportional to the pH value used and therefore errors in the pH values used will cause equivalent errors in SIC calculation.

As has already been noted (see pH), field and laboratory pH determinations could differ greatly and field determinations of pH should be used as they are more representative. Also, water with a high content of carbonate species, such as the samples examined during the present study, tends to lose CO_2 with time and with increasing temperature, as in a laboratory, causing an increase in pH. As noted earlier, only laboratory pH values are available for this study.

Errors in calcium and bicarbonate concentration determination and the theoretical temperatures used for the calculation of the K_{iap} will also affect the result.

The activity (active concentration) of Ca^{++} diminishes in water with a high total ionic concentration (>500-800 ppm), as a certain percentage of the total calcium concentration reported is in the form of complex ions (eg $CaSO_4$) and not as bicarbonate.

In view of all the above noted possible sources of error, it becomes clear that the results of an investigation using saturation indices are equivocal. Also, given the complicated relationship between the river, aquifer and springs, it was thought that such a study must be of limited usefulness, especially since the aquifer samples were taken from pumping wells which should be significantly oversaturated, due to pressure reduction in the aquifer (Lawrence _et al._ 1976).

13.2 Major ion hydrochemistry

Calcium (Ca):

Calcium is one of the most common ions in the groundwater and is the dominant cation in all water-types in the area.

Limestone mainly consists of calcium carbonate and is, therefore, a massive source of calcium in karstic aquifers. Also, in the sandstones of the flysch and other marine clastic rocks, the matrix consists mainly of $CaCO_3$ and is also a source of calcium for groundwaters.

Calcium carbonate is relatively insoluble in pure water, (at 23°C only 13 ppm of calcium carbonate or 5.4 ppm as calcium are dissolved) (Davis and de Wiest 1966). In the presence of hydrogen ions (low pH conditions), the solubility of the $CaCO_3$ is highly increased, as the insoluble $CaCO_3$ is converted into the relatively soluble bicarbonate which goes into solution according to the equation

$$CaCO_3 + H^+ \rightleftharpoons Ca^{++} + HCO_3^-$$

The dissociation of carbonic acid is the main source of H^+ in most natural waters, as shown by the following equations:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$
$$HCO_3^- \rightleftharpoons H^+ + CO_3^-$$

As long as sufficient quantities of CO_2 are available, the first step of dissociation takes place. The second stage only occurs when the pH is higher than 8.2.

In most natural waters, the quantity of CO_2 in the system (CO_2 ± H_2O ± $CaCO_3$) is the most important factor affecting the calcium content in the water. If CO_2 is added, solution of $CaCO_3$ continues. If CO_2 is removed, the $CaCO_3$ precipitates. The formation of travertine ($CaCO_3$) at springs, openings and caves is due to the escape of CO_2 to reach equilibrium with the atmospheric pressure of CO_2.

Rain water dissolves CO_2 from the air. The partial pressure of CO_2 in the air is of the order of 3×10^{-4} atmospheres (atm) assuming a CO_2 content of 0.003%. With no more CO_2 than that which can be obtained from contact with air, surface water could contain only about 20-30 ppm of Ca or 74 ppm of $CaCO_3$ at saturation at 10°C (Adams and Swinnerton 1937).

As the $CaCO_3$ content in most natural waters is much higher than this, additional sources of CO_2 must provide the necessary amount. One such source is the activity and decomposition of organic matter, both animal and vegetable, which cause a considerable increase in the concentration of the CO_2 in the water percolating down to the water table through the soil zone or flowing over it.

The amount of CO_2 in soil zone air has been estimated in various ways and conflicting results were reported. Adams and Swinnerton (1937) report that the CO_2 content in the soil air is 1-5% and is capable of dissolving 174-275 mgr/l $CaCO_3$ (70-110 mgr/l as Ca^{++}), while Schoeller (1955) suggests that the water which percolates through the soil may contain 20-50 mgr/l of free dissolved CO_2 which can bring into solution 150-300 mgr/l of $CaCO_3$.

Therefore, groundwater infiltrating into limestone terrains becomes more aggressive and has a higher Ca^{++} concentration after it has passed through a soil/vegetation layer. It can also be observed that the dissolution of bare limestone outcrops is slower than that of limestone with a vegetation and/or soil cover.

The amount of $CaCO_3$ held in solution depends on the partial pressure of CO_2 and on the temperature, an increase in which leads to a slight increase in the absolute solubility of the $CaCO_3$, although a rise in temperature does, in fact, decrease the solubility of CO_2 gas and, in due course, reduces the total dissolved $CaCO_3$ (Burdon and Papakis, 1963).

Evaporation losses tend to concentrate most ions in solution but, as the amount of CO_2 is dependent only on its partial pressure, evaporation does not affect Ca^{++} concentration in this way if temperature stays stable.

The presence of other salts (K and Na) in solution increases the solubility of $CaCO_3$ (Hem, 1970).

	Alfios River	Aquifer 1 Subzone A	Aquifer 1 Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
Ca^{++} (mgr/l)	67-112 (*) 84 (**)	71-88 77	52-63 57	88-98 92	67-75 71	92-96 94	69-80 72

Table 13.4 Min-max(*) and mean(**) values of the Ca^{++} content in the various water bodies.

Table 13.4 gives the Ca^{++} concentration in all waters encountered in the study area. Calcium is the main cation in all the water types examined but, whatever its absolute concentration, it ranged within low values (50-100 mgr/l). The lowest calcium content is noticed in aquifer 1 (subzone A) and the highest in the Korbitsi spring, aquifer 2 and the Alfios river during the summer. Seasonal variations in calcium content were only observed in the Alfios river, due mainly to the changes in the temperature of its water which controls the partial pressure of CO_2 in solution.

Magnesium (Mg^{++})

Magnesium is generally found in all natural water in lesser concentrations than is calcium.

The main sources of magnesium from sedimentary rocks are dolomite $(MgCa)CO_3$ and magnesite ($MgCO_3$). Pure dolomite contains 21.7% calcium and 13.1% magnesium by weight and, therefore, the Ca/Mg ratio in pure dolomite is 1.65.

All limestone does, in fact, contain some magnesium, so water solution of limestone commonly contains Mg as well as Ca. Data concerning the Mg content of the Upper Cretaceous limestones of the Pindos zone are not available from Greek sources.

The geochemistry of magnesium carbonate is quite similar to that of calcium. Magnesium carbonate does not dissolve easily in pure water, although it is more soluble than is calcium carbonate. When water is in equilibrium with atmospheric CO_2, about 190 mgr/l of Mg will remain in solution (Davis and de Wiest 1966). The solubility of the magnesium carbonate increases in the presence of CO_2 in solution, as with calcium carbonate, as it is converted into the readily soluble bicarbonate. Magnesium carbonate is more easily dissolved in the presence of sodium salts.

The solubility of pure magnesium carbonate is much greater than that of calcium carbonate but, despite the higher solubility of most of its compounds, magnesium is generally found in lesser concentrations in natural water than is calcium, probably because of the lesser availability of magnesium.

Magnesium is present in low concentrations in all water-sources of the area (see Table 13.5).

	Alfios River	Aquifer 1 Subzone A	Aquifer 1 Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
Mg^{++}	9.7-18.0 (*)	11.2-17.5	11.2-14.8	8.3-12.6	11.2-14.1	2.4-4.9	0.5-3.9
(mgr/l)	14.0 (**)	14.2	13.4	10.2	12.6	3.4	2.4

Table 13.5 Min-max(*) and mean(**) values of the Mg^{++} content in the various water-bodies.

It was found that the Alfios river, the aquifers and the Panagia spring have a higher Mg content (10-14 mgr/l), while the Korbitsi and Kefalovrisi springs exhibit a much lower Mg content (2-4 mgr/l). This will be discussed in detail in Chapter 14.5.

Sodium (Na^+)

All natural water contains measurable quantities of sodium. The primary sources of sodium in natural waters are the products of the weathering of igneous and metamorphic rocks. Clay minerals and other sedimentary rocks also release sodium. In limestone and in carbonate rocks generally, there is little sodium precipitated during their sedimentation. Sodium salts ($NaCl$, $NaNO_3$, Na_2CO_3) are very soluble and only precipitate when concentrations of several thousand ppm are reached (Davis and de Wiest, 1966).

Through base-exchange mechanisms, sodium replaces other, mainly divalent, cations such as Ca and Mg, the extent of which is dependent on the relative concentration of the ions.

Sodium is present in the waters analysed in concentrations ranging from 10.6 mgr/l (Alfios river) to 3.7 mgr/l in aquifer 2 (subzone B) (see Table 13.6). It is to be expected that the Alfios river should have higher values in sodium concentration because it is surface water, especially during summer when most of its base-flow derives from the retained groundwater in the terrace gravel-bodies which also has a high Na^+ content (see Section 14.4) which increases due to evaporation. In most cases, Na^+ is in balance with the equivalent Cl^-.

	Alfios River	Aquifer 1 Subzone A	Aquifer 1 Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
Na^+ (mgr/l)	8.0-16.6 (*) 10.6 (**)	4.6-7.1 5.3	3.2-4.8 3.7	8.0-10.3 8.7	3.9-5.7 4.8	3.5-4.6 4.1	3.4-6.0 4.5

Table 13.6 Min-max(*) and mean(**) values of the Na^+ content in the various water-bodies.

Potassium (K^+)

Although potassium is of the same availability as sodium for solution in nature, potassium is always one of the minor constituents in natural water. The low level of K^+ concentration is due to the fact that, unlike Na^+, which remains in solution after it has leached from minerals, K^+ is easily recombined with other products of weathering to form clay and clay-type minerals (Hem, 1970).

Base-exchange ion mechanisms and absorption by clays are also important processes in the removal of K^+ from natural water, although they were not detected to take place in the waters present in the area. Potassium is found in all water sources of the area in very small amounts. The Alfios river has higher potassium values, especially during the summer, for the same reasons suggested for sodium.

Bicarbonate (HCO_3^-) and carbonate (CO_3^{--})

Bicarbonate is usually the primary anion in groundwater and is derived from CO_2 in solution, derived, in turn, from the atmosphere and organic processes in the soil and the solution of carbonate in the aquifer itself.

Alkalinity is the effect of all anions which form acids that are only weakly dissociated in solution and thus enter into hydrolysis reactions and is expressed in terms of equivalent titriable amounts of bicarbonate, carbonate and hydroxide ions (Hem, 1970).

Alkalinity of the water can be equated with bicarbonate concentration, since dissociation of bicarbonate to carbonate ions only occurs largely above a pH of 8.2 (see also Ca^{++}). pH values greater than 8.2 were not encountered during the present study, except in one instance in the Alfios river.

Chloride, sulphate and nitrate ions do not affect alkalinity. Alkalinity is, therefore, equivalent to the temporary or carbonate hardness.

Bicarbonate was found to be in high concentration in all water analysed (Table 13.7). Bicarbonate is the main anion and was found in much higher concentrations than other anions. Most carbonates held in solution by the groundwater and the Alfios river are in bicarbonate form.

Bicarbonate concentration tends to be lower in the Alfios river, in which seasonal variations are noted, and also in subzone B of aquifer 1, while it is higher in the Korbitsi spring.

	Alfios River	Aquifer 1 Subzone A	Aquifer 1 Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
HCO_3^- (mgr/l)	150-247 (*) 206 (**)	265-296 281	213-230 224	255-288 265	253-279 265	281-305 293	212-237 223

Table 13.7 Min-max (*) and mean (**) values of the bicarbonate content in the various water-bodies.

<u>Sulphate (SO_4^{--})</u>

One of the main sources for SO_4^{--} in surface water and groundwater is rain water, in which SO_4^{--} is one of the major ions. Chilingar (1956) reports that the average sulphate content in the rain over the USSR was 9.2 mgr/l and Verry (1983) quotes the sulphate content in rain over large areas of North America as ranging from 1.5 to 4.2 mgr/l.

The combustion of lignite on an industrial basis at Megalopolis adds sulphur dioxide and trioxide to the air, some of which is brought down by rain as a weak solution of sulphuric acid, and it is, therefore, to be expected that the SO_4^{--} content in precipitation over the Megalopolis basis would be higher than the average.

Lignite beds contain a high level of sulphur content, of 1 to 17% (Marinos <u>et al.</u> 1959) and clays also contain considerable amounts of ferrous sulphate. The lignite and clays are, therefore, responsible for the high SO_4^{--} content in the local water, especially in the Alfios river.

Most of the common metallic cations form, in conjunction with the sulphate ion, readily soluble compounds which are chemically stable in most natural water environments.

Extremely high values of sulphate were measured in the Alfios river, where a value of 184 mgr/l was noted, and also in aquifer 2 (Table 13.8). Here, a significant portion of the sulphate is associated with Mg, in the form of $MgSO_4$. Aquifer 1 and the springs have a lower sulphate content. Sulphate values only exhibit considerable seasonal variations in the Alfios river water.

	Alfios River	Aquifer 1 Subzone A	Aquifer 1 Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
SO_4^{--} (mgr/l)	38.4-184 (*)	10.6-32.6	8.2-18.2	43.2-62.9	5.8-13.0	1-5.3.0	3.8-5.3
	96.5 (**)	15	12	52	10.1	3.4	4.6

Table 13.8 Min-max (*) and mean (**) values of the sulphate content in the various water-bodies.

Chloride (Cl^-)

Chloride, present in all natural waters of the area in small amounts, is mainly derived from initial precipitation, since evaporite deposits or saline intrusions, both important potential sources responsible for high concentrations of Cl^-, do not occur in the study area.

Limestone seems to contain a small amount of chloride but this must be higher in the basin sediments, as is indicated by the higher chloride content in the Alfios river water.

As all chloride salts are highly soluble and generally free from the effects of exchange, adsorption and biological activity, Cl^- is rarely removed from water by precipitation through natural processes.

Chloride concentration was low in all the water examined (Table 13.9), ranging between 20 mgr/l (Alfios river) and 5.3 mgr/l (Korbitsi spring).

	Alfios River	Aquifer 1 Subzone A	Aquifer 1 Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
Cl^-	8.9-19.5 (*)	8.9-14.2	5.3-7.1	8.9-14.2	7.1-10.6	5.3-8.9	7.1-12.4
(mgr/l)	13.1 (**)	10.6	7.1	12.4	8.8	7.1	8.5

Table 13.9 Min-max(*) and mean(**) values of the chloride content in the various water-bodies.

A similar pattern of contribution to that of the sulphate ion is shown in all the waters of the area by the chloride ion.

Nitrate (NO_3^-)

Nitrogen occurs in water in various forms, depending on the degree of oxidation, nitrate being its completely oxidised state.

The amount of nitrates in precipation is very small. In groundwater, nitrates originate mainly from organic, predominantly bacterial, activity and decomposition and from human and animal waste disposal, nitrogen being one of the most essential elements in all living organisms.

The application of soluble chemical fertilizers, such as nitrogen and ammonia, is also a primary source of excessive nitrate in water. Chemical pollutants such as nitrate easily enter superficial aquifers during the recharge period (Walker, 1973).

Nitrogen, in its various forms, carries considerable significance as an indicator of organic pollution (Hem, 1970).

The nitrate concentration in all the samples analysed is found to be much below the World Health Organisation recommended limit of 11.3 mg/l as N (or 45 mg/l as NO_3^{-2}) (Table 13.10).

	Alfios River	Aquifer Subzone A	Aquifer Subzone B	Aquifer 2	Panagia Spring	Korbitsi Spring	Kefalovrisi Spring
NO_3^- (mgr/l)	0.0-21.7 (*) 6.2 (**)	0.0-15.5 5.0	0.0-0.6 0.0	1.2-12.4 3.7	0.0-0.6 0.6	0.0-6.8 1.9	0.0-1.8 0.6

Table 13.10 Min-max (*) and mean (**) values of the nitrate content in the various water bodies.

CHAPTER 14: AREAL VARIATION IN THE WATER CHEMISTRY

14.1 Karstic aquifer hydrochemistry

All samples analysed were obtained from wells while they were being pumped. Since the water abstracted by pumping is derived mainly from zones with the highest transmissivity, these samples should be considered as fully representative of the water of the aquifer. It should, however, be noted that, when water moves into the area of influence of a pumping well, the marked sudden change in pressure head causes at least some calcium carbonate to precipitate (Hem, 1961).

Areal variation of total ionic concentration, as well as the content of individual ions, was detected in the water of the aquifers. When the results of the analyses are plotted on a Piper diagram (Fig 14.2), which is a graphical representation of the contribution of the major ions, two principal types of groundwater can be clearly recognised, corresponding to aquifers 1 and 2 as they are defined in the earlier sections (Fig 14.1).

Table 14.1 gives the average contribution (in percentages*) of the various ions to the chemical composition of both aquifers.

	Cations %			Anions %			
	Ca^{++}	Mg^{++}	Na^{++}	HCO_3^-	Cl^-	SO_4^{--}	NO_3^-
Aquifer 1	71	25	4	88	5	6	<1
Aquifer 2	79	14	7	75	6	18	1

Table 14.1 Chemical composition (in percentages) of the TDI content (meq/l) of the main aquifers in the Kyparissia field.

(*) All percentages quoted in this Chapter refer to total milligramme equivalents per litre. Cations plus anions total 100%.

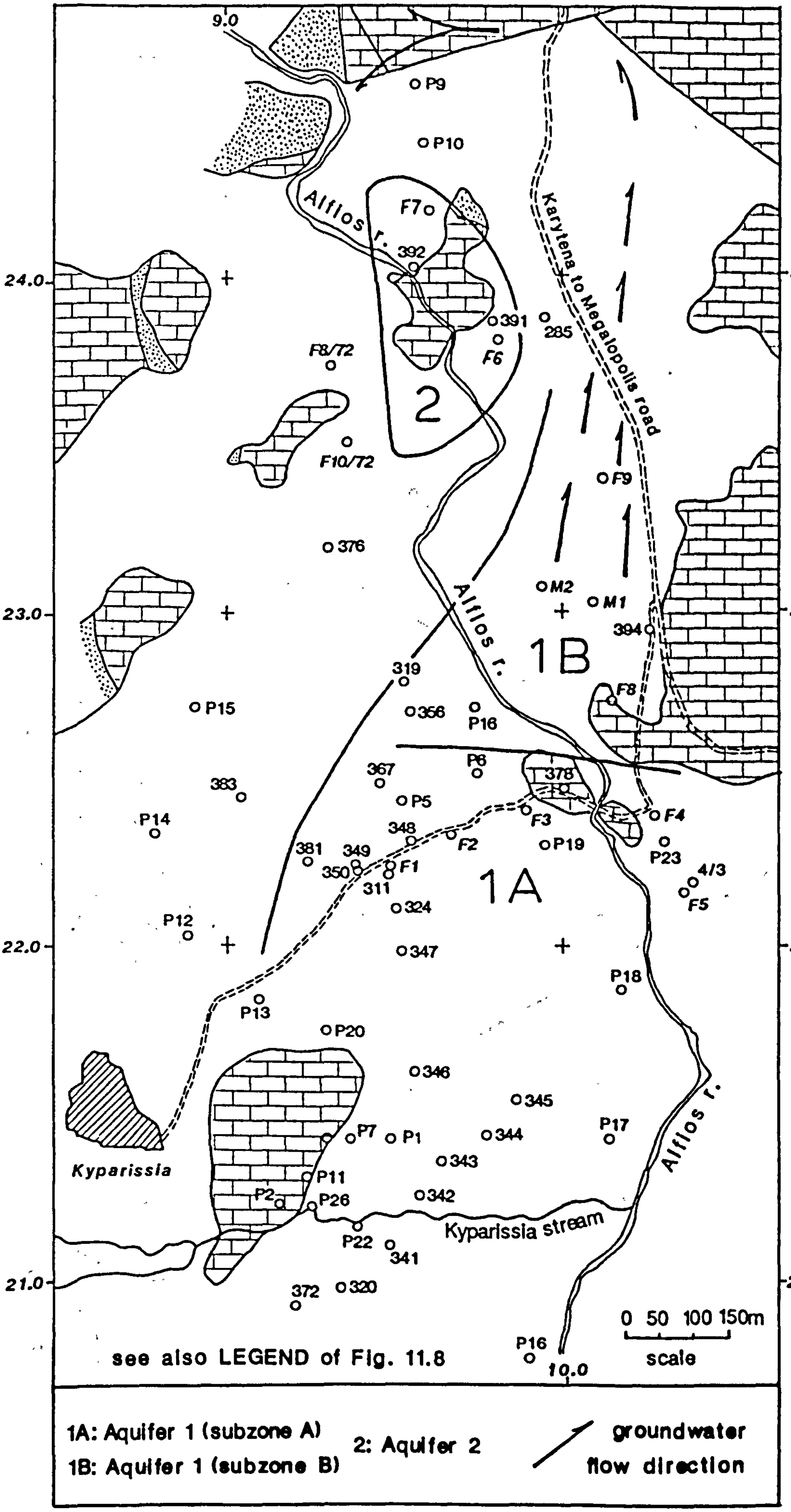


Fig 14.1 Definition of the extent of the hydrochemical subzones A and B within aquifer 1.

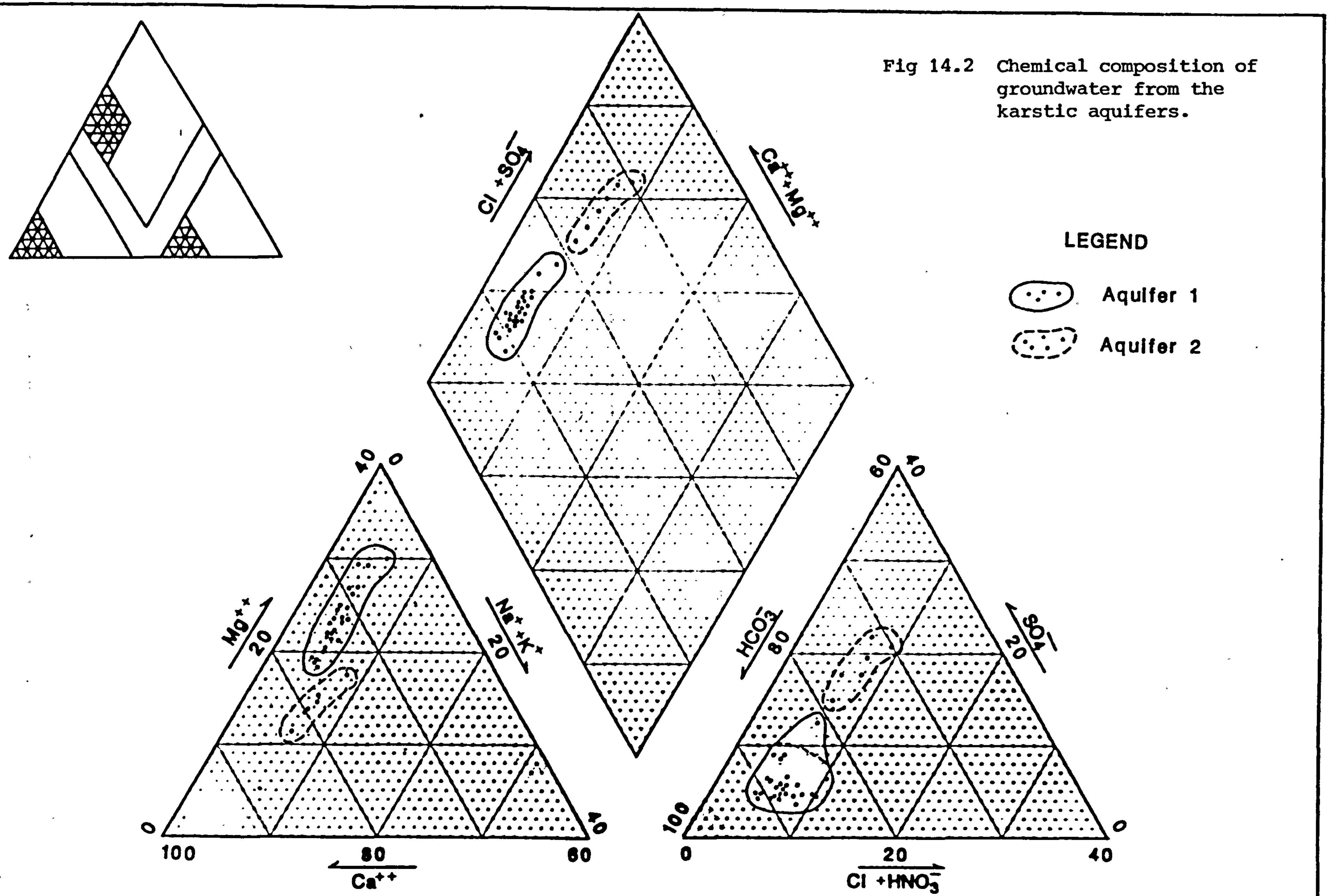


Fig 14.2 Chemical composition of groundwater from the karstic aquifers.

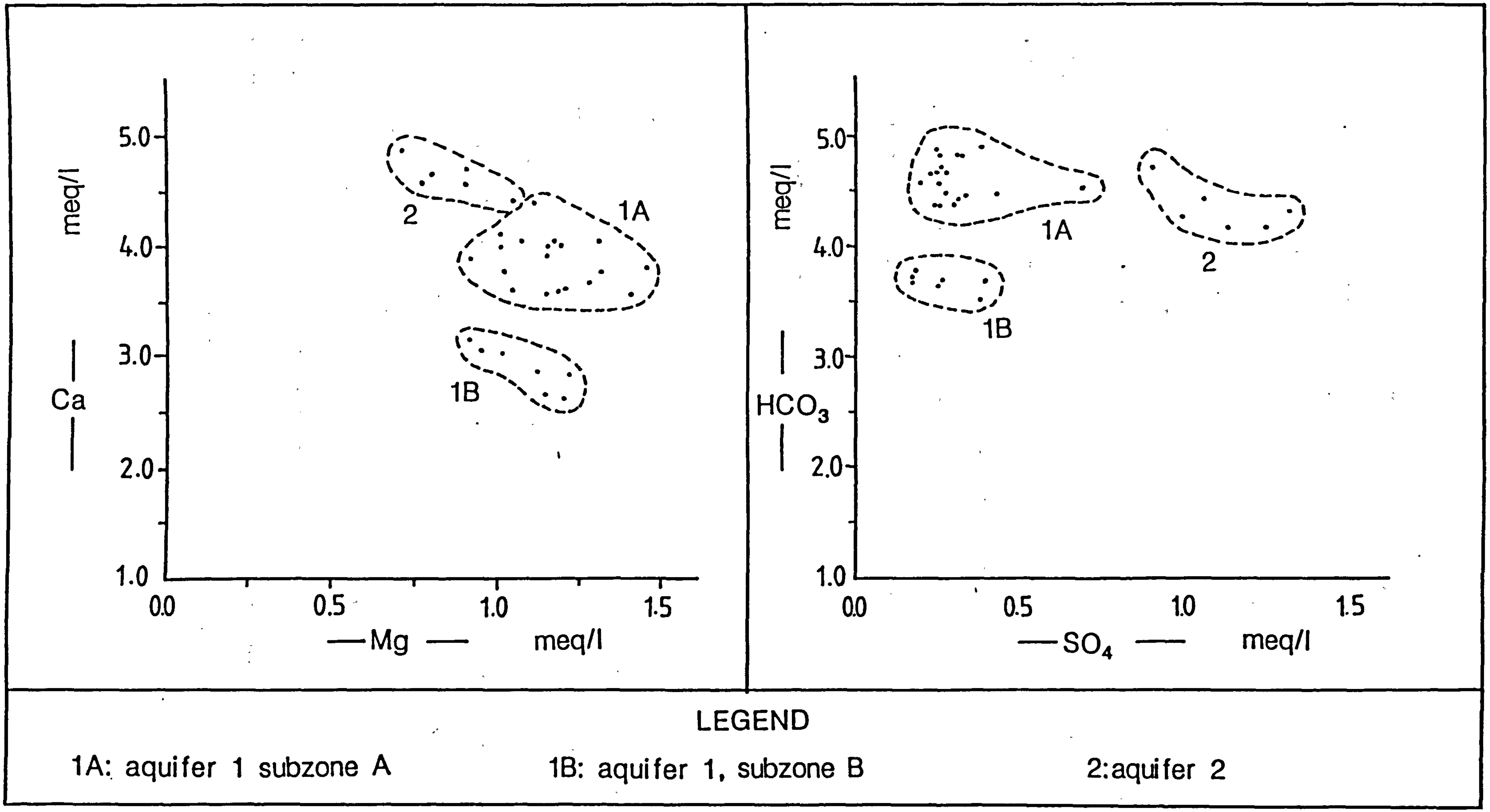


Fig 14.3 Ca^{++}/Mg^{++} and HCO_3^-/SO_4^{--} content in groundwater of the karstic aquifers in the Kyparissia area.

i) Aquifer 1 water is of $Ca/Mg:HCO_3$ type groundwater, where the Ca^{++} ion constitutes the dominant cation with a considerable level of Mg^{++} and with a very high HCO_3^- content.

ii) Aquifer 2 water is characterised as being of $Ca/Mg:HCO_3/SO_4$ type. The SO_4^{--} ion contribution to the anion composition is significantly higher than in the aquifer 1.

In both aquifers the relative ionic abundances are Ca>>Mg>Na and $HCO_3 \gg SO_4 > NO_3$. This is to be expected, as these aquifers are developed within a carbonate, mainly limestone-calcite, environment.

Aquifer 1 is subdivided into two subzones, A and B, this division being based on the TDI content of their groundwater. Subzone B, which is the lower range one, has a TDI content 22% lower than subzone A. This decrease in the TDI content is stoichiometric in all the individual ions, as can be seen from Tables 14.2 and 14.3 and also from Fig 14.3.

Aquifer 1

The first group of water types includes water originating from the wells F1, F2, F3, F4, F5, F8 and F9 and therefore coincides with aquifer 1, as defined earlier (Section 11.4).

The groundwater of this aquifer is of $Ca/Mg:HCO_3$ type, with other ions being present in small amounts (always less than 10% meq/l of the total cations or anions).

Ca^{++} is the dominant cation. The average Ca^{++} content is just over 70%. Magnesium is always present in significant amounts and represents about 25% of the total. The Na^+ and K^+ cations make up 4% and 3% respectively. Of the various anions, bicarbonate dominates, amounting to

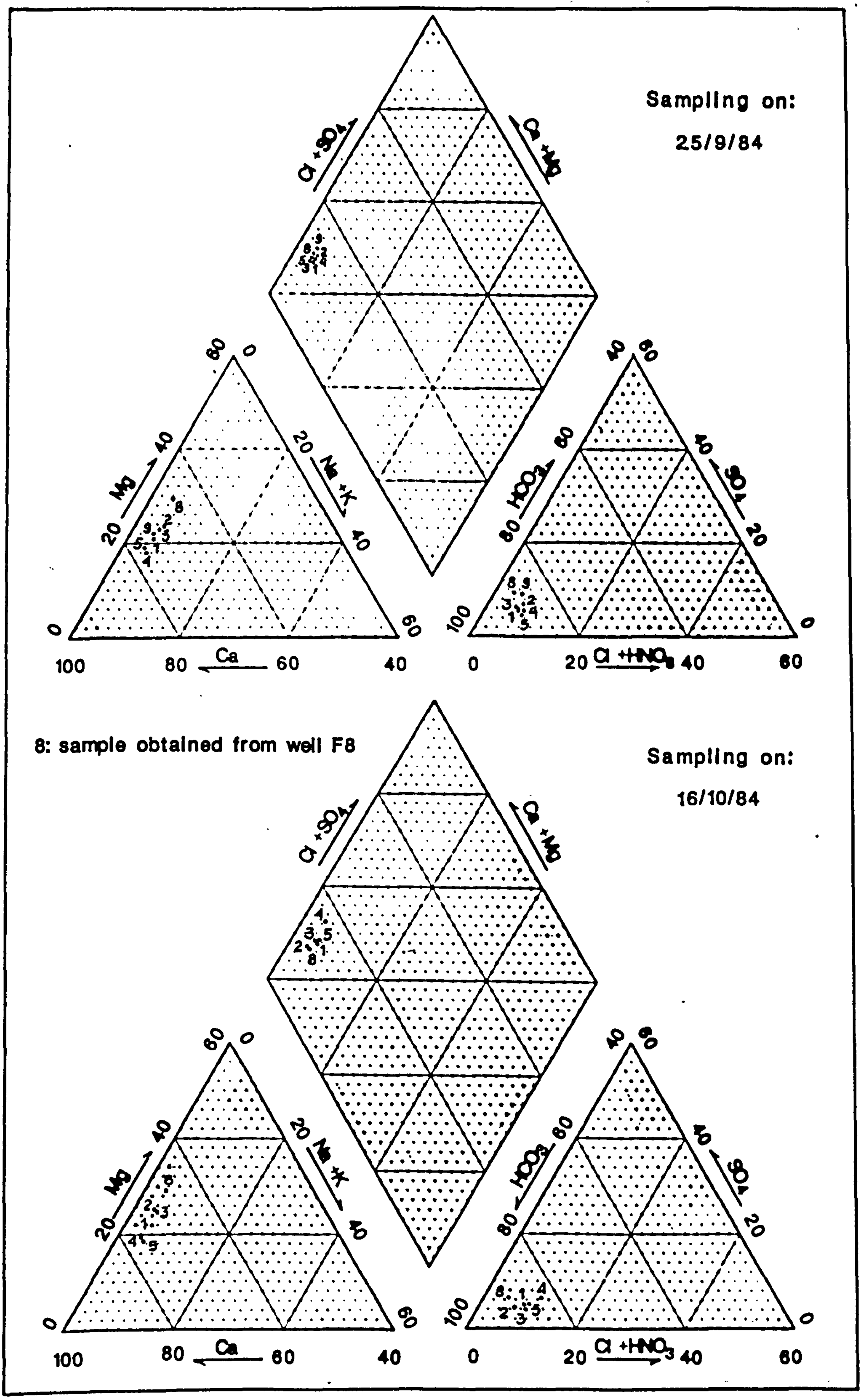


Fig 14.4 Chemical composition of groundwater from aquifer 1.

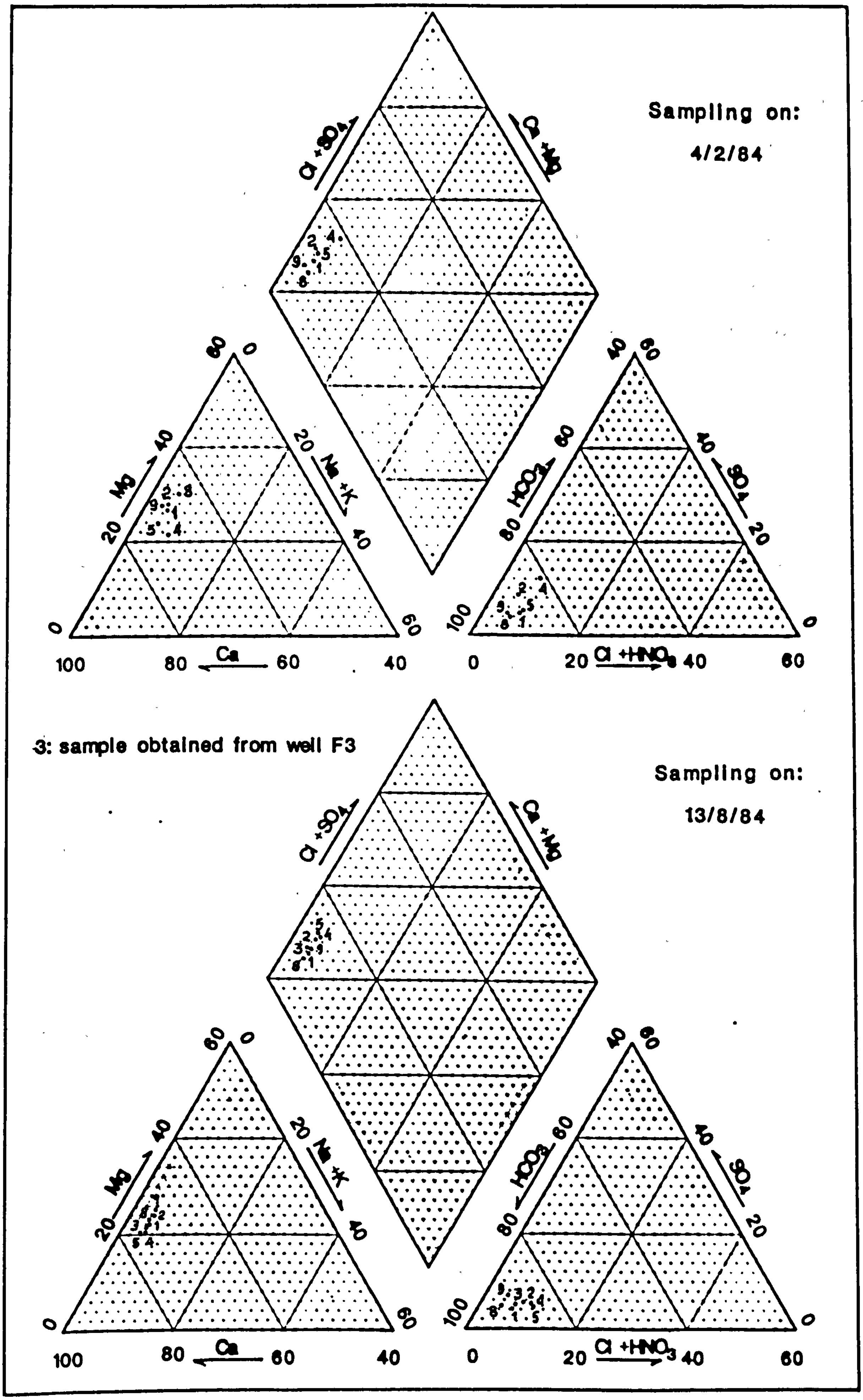


Fig 14.5 Chemical composition of groundwater of aquifer 1.

a little less than 90%. Chlorides and sulphates are of lesser importance, accounting for 5 to 6%, while nitrates are present only in small amounts and account for less than 1% (Table 14.1).

From the four diagrams (Figs 14.4 and 14.5) representing the chemical composition of the groundwater of aquifer 1 at four different times in the year, a seasonal invariability in the chemical composition of the groundwater is evident.

If, however, the absolute values of the ions or the TDI content are considered, a further division into two sub-groups of water, representing two different areas of aquifer 1 can be established. These two types of groundwater have the same chemical composition as far as percentages are concerned but subzone B shows distinctly lower values of invididual and total ionic concentrations than subzone A.

An interpretation of this evolution in the water chemistry will be given in Section 14.5.

Subzone A

This subzone comprises the wells F1 to F5 and covers the area west and south-east of the Kyparissia bridge over the Alfios river.

As seen in the later Section 14.5, it represents the recharge area for aquifer 1, through which the Alfios river percolates and the limit of subzone A can, therefore, be defined as the limit of this recharge area south of and around the Kyparissia bridge (Fig 14.1).

Groundwater from this subzone is of Ca/Mg:HCO_3 type. The average ionic concentrations of the individual ions, as well as the TDI content of the water of the subzone, are given in Table 14.2.

mgr/l										Hardness in $CaCO_3$ ppm		
Cations					Anions							
Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Total cations	Total anions	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Non permanent	Permanent	Total
77	142	5.3	0.8	97	311	281	10.6	15	5	231	21	252

Table 14.2 Chemical composition and hardness values of the groundwater of subzone A of aquifer 1 (mean values of the samples obtained).

The total determined dissolved solids are found, on average, to be about 400 mgr/l. This relatively high value among the groundwaters of the karstic aquifers developed in the area is principally due to the abundant presence of calcium bicarbonate in solution. This high concentration of bicarbonate is also reflected in the high non-permanent (carbonate) hardness which, for this subzone, has a mean value of 231 ppm (as $CaCO_3$) which causes it to fall into the category of hard water.

The Ca^{++}, Mg^{++} ions (expressed in meq/l) are balanced by the HCO_3^- ions, while the Ca^{++}/Mg^{++} ratio is 3.3 (amounts expressed in meq/l) or 5.4 (when amounts are expressed in mgr/l), indicating a limestone source for the carbonate. The HCO_3^-/SO_4^{--} ion ratio is 14.87 and 18.73 respectively for the water of this subzone (Fig 14.4).

The pH values measured were around 7.6, which shows that the water in this subzone of aquifer 1 is relatively aggressive and hence able to dissolve carbonate rocks (see Section 13.1).

A seasonal stability of the chemical composition of the water of this subzone can be established, as is seen in the plots of the chemical analyses of water samples taken (Figs 14.6 and 14.7). The samples taken from the wells F1 and F4 do, however, show a somewhat higher ionic concentration than the others.

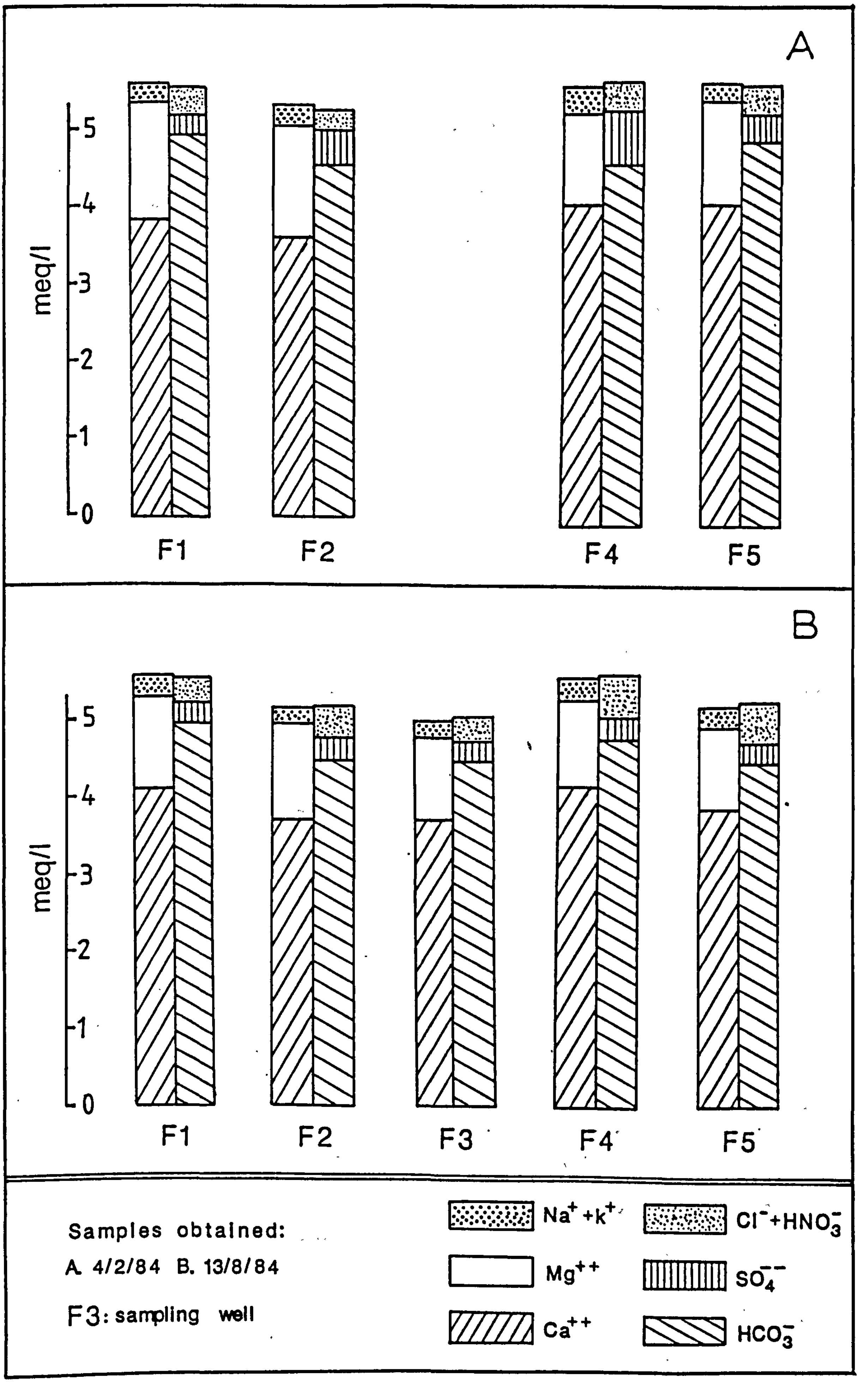


Fig 14.7 Chemical composition of groundwater from subzone A of aquifer 1.

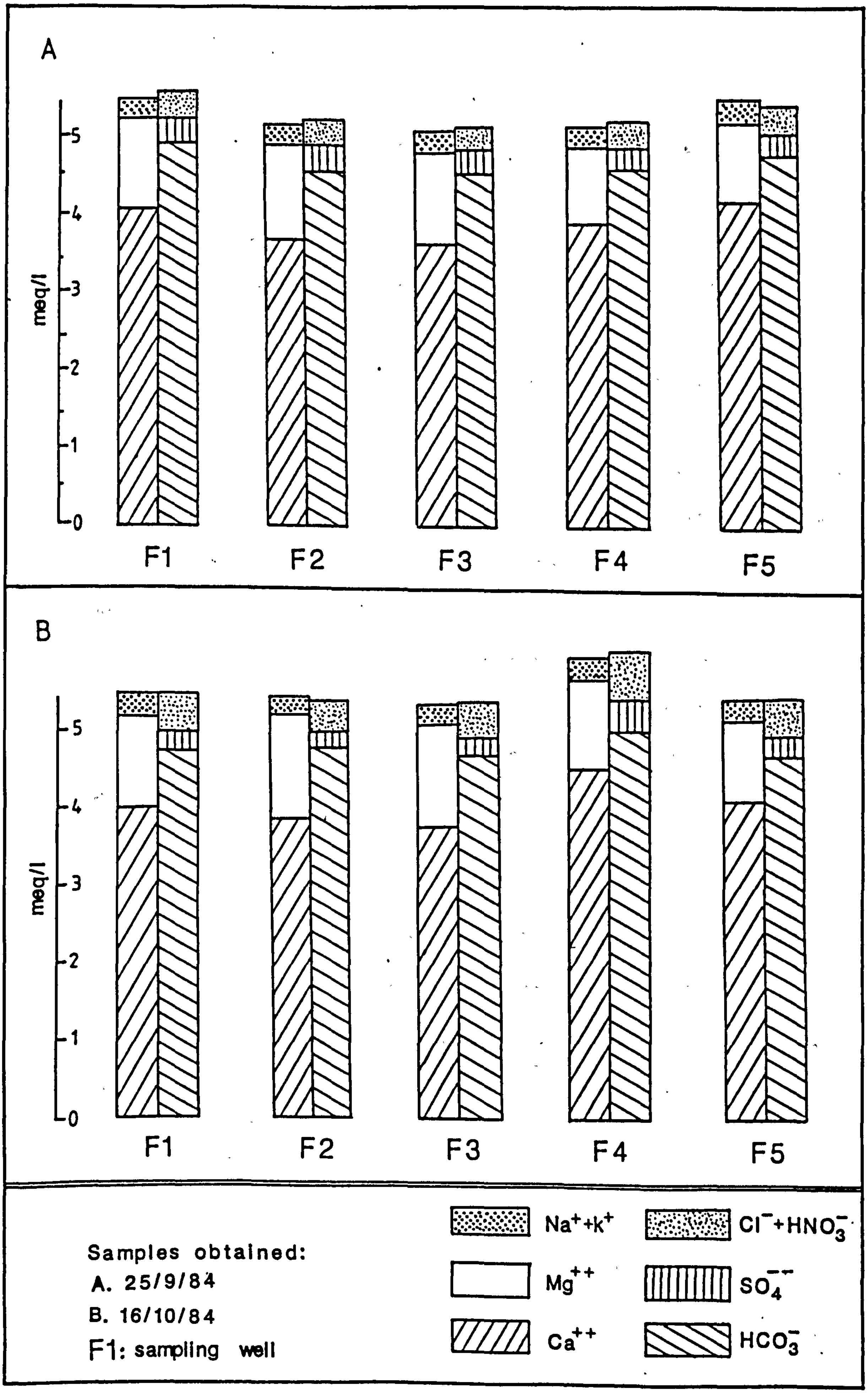


Fig 14.7 Chemical composition of groundwater from subzone A of aquifer 1.

Subzone B

This subzone corresponds to the area around the wells F8 and F9, which is to be found on the eastern side of the Alfios river, north of the Kyparissia bridge. It seems probable that subzone B also covers a limited area to the north of the Kyparissia bridge (Fig 13.1), although this cannot be proved due to lack of data.

The groundwater from this subzone of aquifer 1 is characterised by a total ionic concentration of 318 mgr/l (or 8.25 meq/l) which is about 20% less than that observed in subzone A of this aquifer. This decrease appears to be largely related to a reduction in the calcium and bicarbonate ion concentrations. There is also a smaller reduction in the concentration of the other cations and anions.

Mixing with groundwater of lower concentrations originating from other aquifers developed in the area seems unlikely, since all the other groundwaters of the area have a higher ionic concentration than the groundwater of subzone B, so it must be assumed that chemical precipitation of calcium carbonate takes place within this subzone (see also Section 14.5).

The water of this subzone is also of $Ca/Mg:HCO_3$ type. The average ionic concentrations and hardness values are given in Table 14.3.

mgr/l										Hardness in $CaCO_3$ ppm		
Cations						Anions						
CA^{2+}	Mg^{2+}	Na^+	K^+	Total cations	Total anions	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Non permanent	Permanent	Total
57	13.4	3.7	0.4	75	243	224	7.1	12	0	184	15	198

Table 14.3 Chemical composition and hardness values of the groundwater of subzone B of aquifer 1 (mean values of the samples obtained during 1984).

The Ca^{++} and Mg^{++} ions are also balanced here by the HCO_3^- anion (3.96:3.67 meq/l respectively), which is the dominant anion (89% on

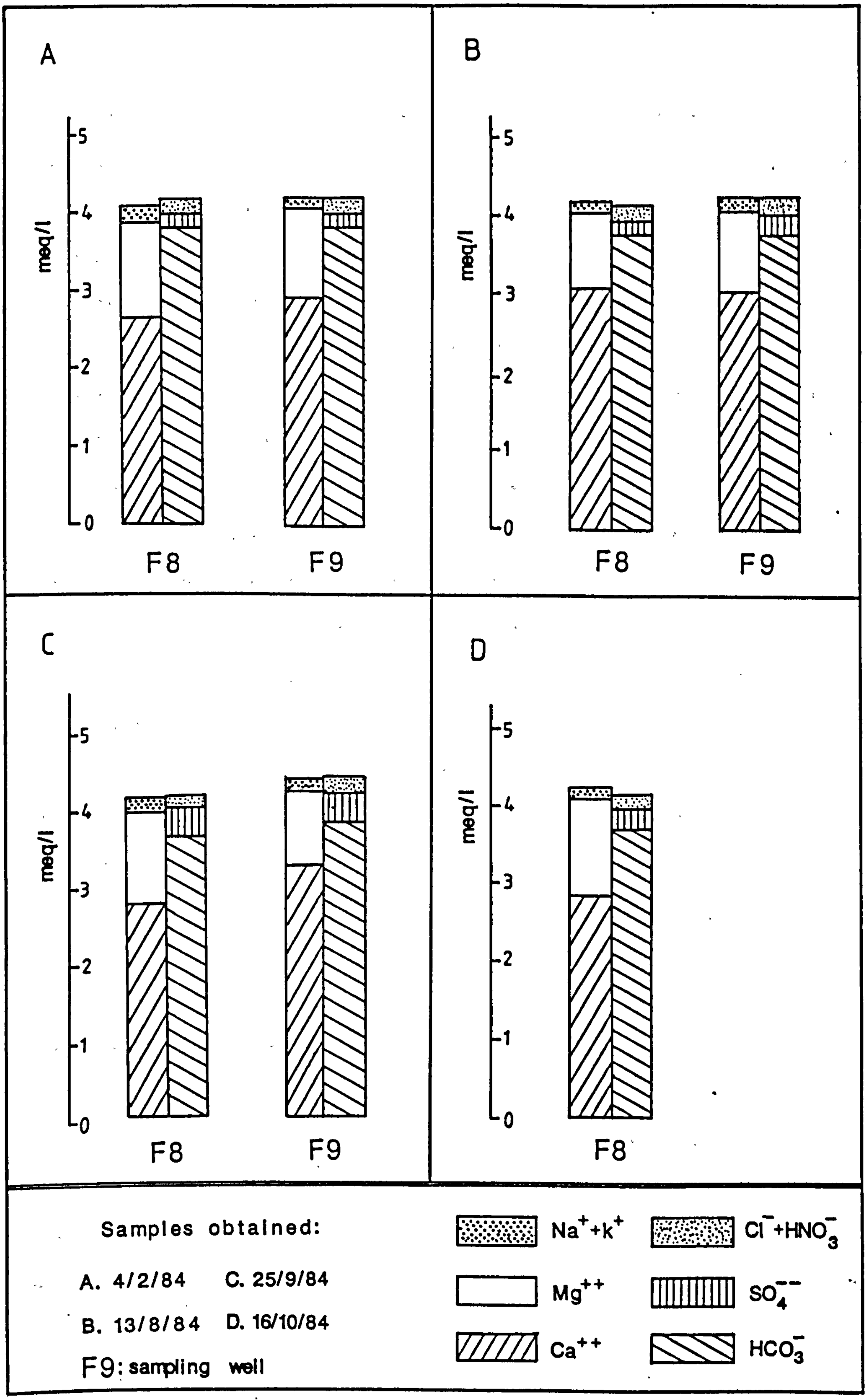


Fig 14.8 Chemical composition of the groundwater from subzone B of aquifer 1.

average) but found in much lower concentration here than in subzone A. The lower ionic concentration is reflected in the hardness values, which are the lowest of any groundwater in this area and show a mean value of 198 ppm (as $CaCO_3$).

The pH values measured in the water of this subzone have an average value of 7.7 which also indicates that, despite the reduction in bicarbonate, the water is still slightly aggressive, due to the presence of weak carbonic acid in solution.

The Ca^{++}/Mg^{++} ratio is 2.6 (amounts expressed in meq/l) or 4.25 (in mgr/l) which is lower than in subzone A, indicating a movement of the water in a limestone (calcite) environment and also a higher reduction in the calcium content in respect of the magnesium. The HCO_3^-/SO_4^{--} ratio, which is 14.68 or 18.66 respectively, is the same as for subzone A (Fig 14.4).

The water of subzone B of aquifer 1 also exhibits a seasonal stability throughout the year, as well as a lack of areal variation in chemical composition through the whole of its extent (Fig 14.8).

Aquifer 2

The second group of water types includes wells F6 and F7 and therefore corresponds to aquifer 2, as defined in the earlier Section 11.4 (Fig 14.1).

Hydrological evidence proves indisputably that this aquifer, which only extends over a small area, is fed by the Alfios river (Chapter 12.2). Chemical processes and changes in the river's water must, therefore, be considered and interpreted when dealing with aquifer 1 (Chapter 10.5).

The mean ionic concentrations and hardness values of aquifer 2 are given in Table 14.4.

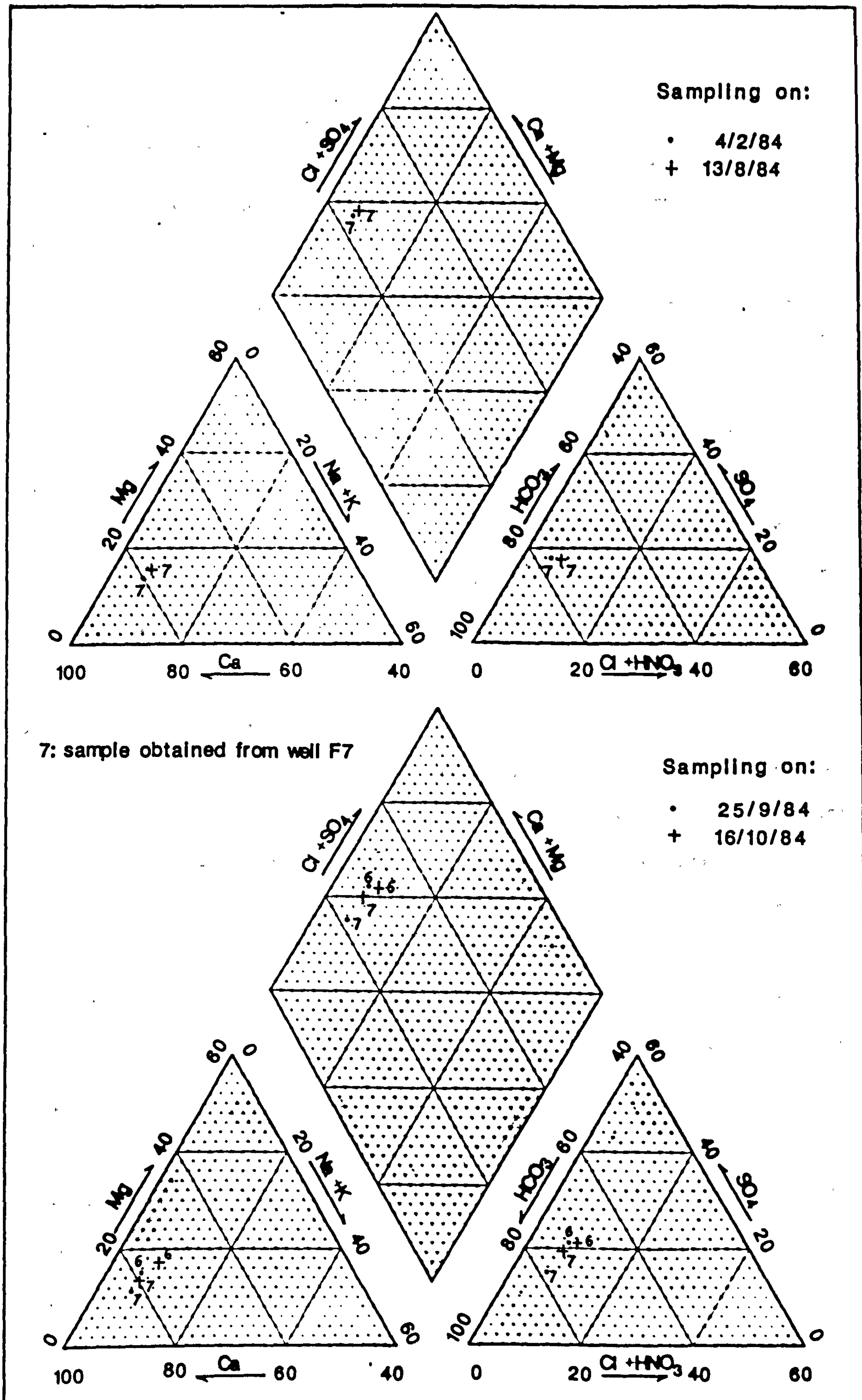


Fig 14.9 Chemical composition of groundwater from aquifer 2.

mgr/l										Hardness in $CaCO_3$ ppm		
Cations					Anions							
Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Total cations	Total anions	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Non permanent	Permanent	Total
92	10.2	8.7	0.8	112	333	265	12.4	52	3.7	218	54	272

Table 14.4 Chemical composition and hardness values of the groundwater of Aquifer 2 (mean values).

The striking feature of the hydrochemistry of this aquifer is its high sulphate content. Even given the predominance of bicarbonate (75% on average), the sulphate here forms a significant percentage of the anionic constitution accounting, on average, for just under 20% of the total. Although calcium bicarbonate is the dominant compound to be found in solution, the calcium and especially the magnesium sulphates are also of considerable significance.

The bicarbonate and sulphate anions, when expressed in meq/l, are usually balanced by the alkaline-earth cations (Ca, Mg) and the chloride anion is approximately balanced by sodium, whose concentration in this aquifer (5.3 mgr/l) is almost twice the mean value in aquifer 1. The same applies to the potassium concentration.

Here, the higher values of sulphate are associated with higher permanent hardness, which has an average value of 54 mgr/l (as $CaCO_3$), the highest noticed in groundwater in the area, which, combined with the non-permanent hardness of an average of 218 mgr/l, makes up a total hardness of 272 mgr/l, showing the water of this aquifer to be the hardest in the area.

The pH values measured in the water of this aquifer had an average value of 7.6 and were slightly lower than those measured in the groundwater of aquifer 1, especially during the dry season (pH 7.5), due

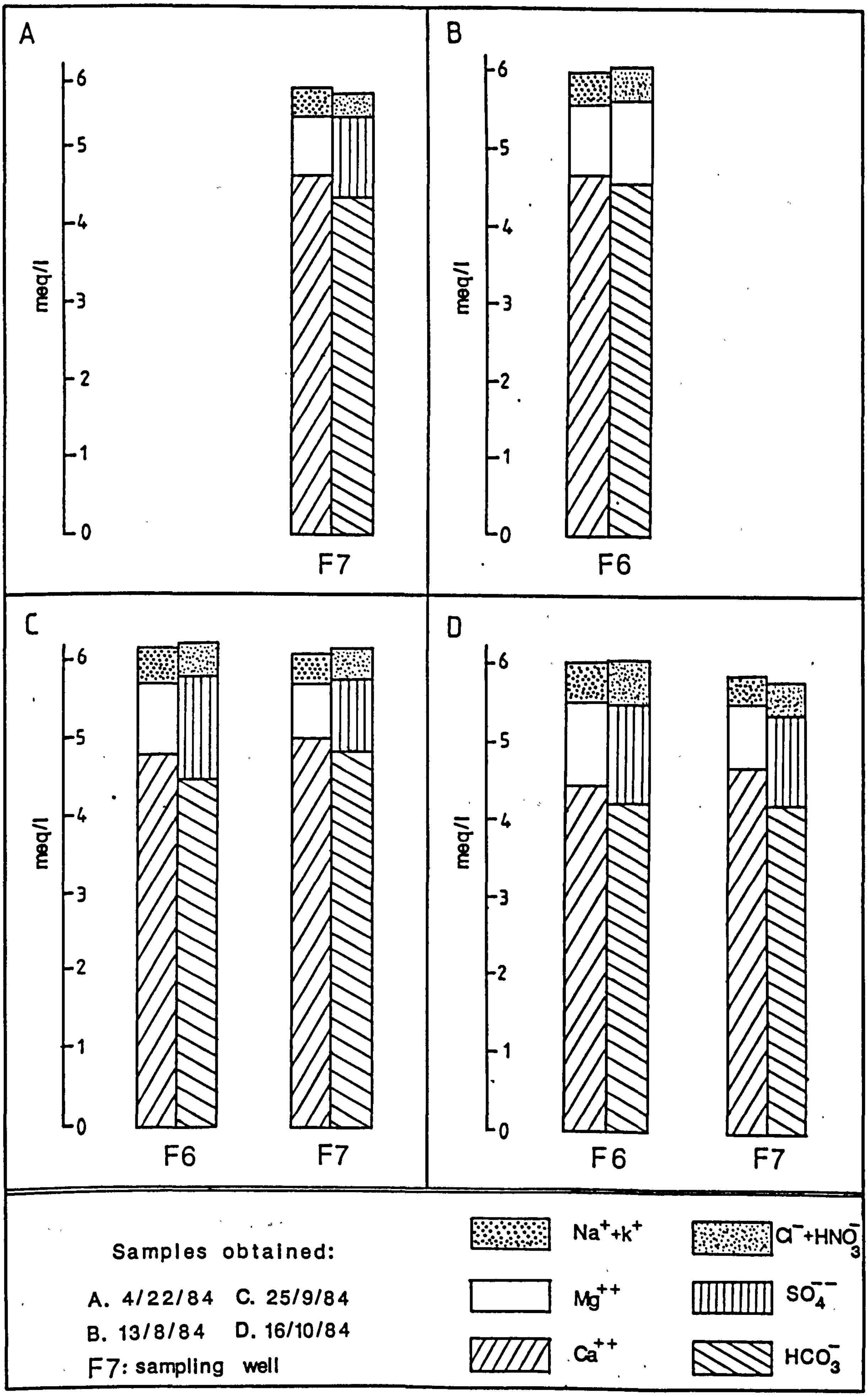


Fig 14.10 Chemical composition of groundwater from aquifer 2.

to the lower contribution of HCO_3^- (carbonic acid) to the anionic constitution.

The Ca^{++}/Mg^{++} ratio in aquifer 2 is 5.46 (when amounts are expressed in meq/l) or 9.0 (in mgr/l), which is much higher than that of aquifer 1, as a result of the low concentration of magnesium (0.84 meq/l on average), in respect of the calcium (4.6 meq/l on average) which are, respectively, the highest values noticed in the groundwater of the area. The HCO_3^-/SO_4^{--} ratio of this aquifer is 4.02 (in meq/l) or 5.1 (in mgr/l), these values being much different from those of aquifer 1. These high values result from the high concentration of sulphate in this aquifer (1.08 meq/l), which is higher than in aquifer 1 (mean value: 0.28 meq/l) (Fig 14.4). The sulphate originates from the Alfios river, by which the aquifer is fed and in which the sulphate is seen to be present in much greater concentrations.

From the plots of the chemical analyses of the water samples taken (Figs 14.9 and 10), it can be seen that there is virtually no seasonal variation in the chemical composition of the water of this aquifer. The well F7, however, which lies a little further away from the area where the Alfios river percolates down to the aquifer than does the well F6, exhibits a slightly higher TDI and sulphate content than the groundwater from the well F6. In contrast, the calcium and bicarbonate concentrations are lower in well F7 than in well F6.

14.2 Spring hydrochemistry

Four springs - ie the Panagia, the Kefalovrisi, the Korbitsi and the Palataki - emerging in the northern part of the Megalopolis basin were also systematically sampled during 1984. A few more water analyses of additional samples taken during 1982 and 1983 are available for the Panagia and Kefalovrisi springs.

By plotting the results of the chemical analyses on a Piper diagram (Fig 14.11), two groups of springs with water of different chemical composition can be clearly distinguished.

The first group includes the Kefalovrisi, Korbitsi and Palataki springs. These three springs, based on a careful evaluation of all field evidence, would appear to be fed only from the discharge of limestone terrains and they show the same water chemistry of $Ca:HCO_3$ type, typical of a karstic system.

The second group includes the Panagia and Opiste Panagia springs, only one chemical analysis being available for the latter. These two springs emerge from opposite sides of a limestone outcrop to the north of the Kyparissia field (Fig 10.7c).

	Cations %			Anions %			
	Ca^{++}	Mg^{++}	Na^{+}	HCO_3^{-}	Cl^{-}	SO_4^{--}	NO_3^{-}
First group of springs	90	5.5	4.5	92	4.5	2.5	<1
Second group of springs	74	21.5	4.5	90	5	4.5	0.5

Table 14.5 Chemical composition (as percentages of the total cations or anions, in epm) of the first and second groups of springs (mean values of the samples obtained during 1984).

As can be seen from Table 14.5, the water from the first set of springs is of $Ca:HCO_3$ type, with calcium bicarbonate being the predominant chemical compound taken into solution, while all the other ions are present as minor constituents.

On the contrary, the water chemistry of the second group of springs, being of $Ca/Mg:HCO_3$ type, differs significantly in its Mg^{++} content

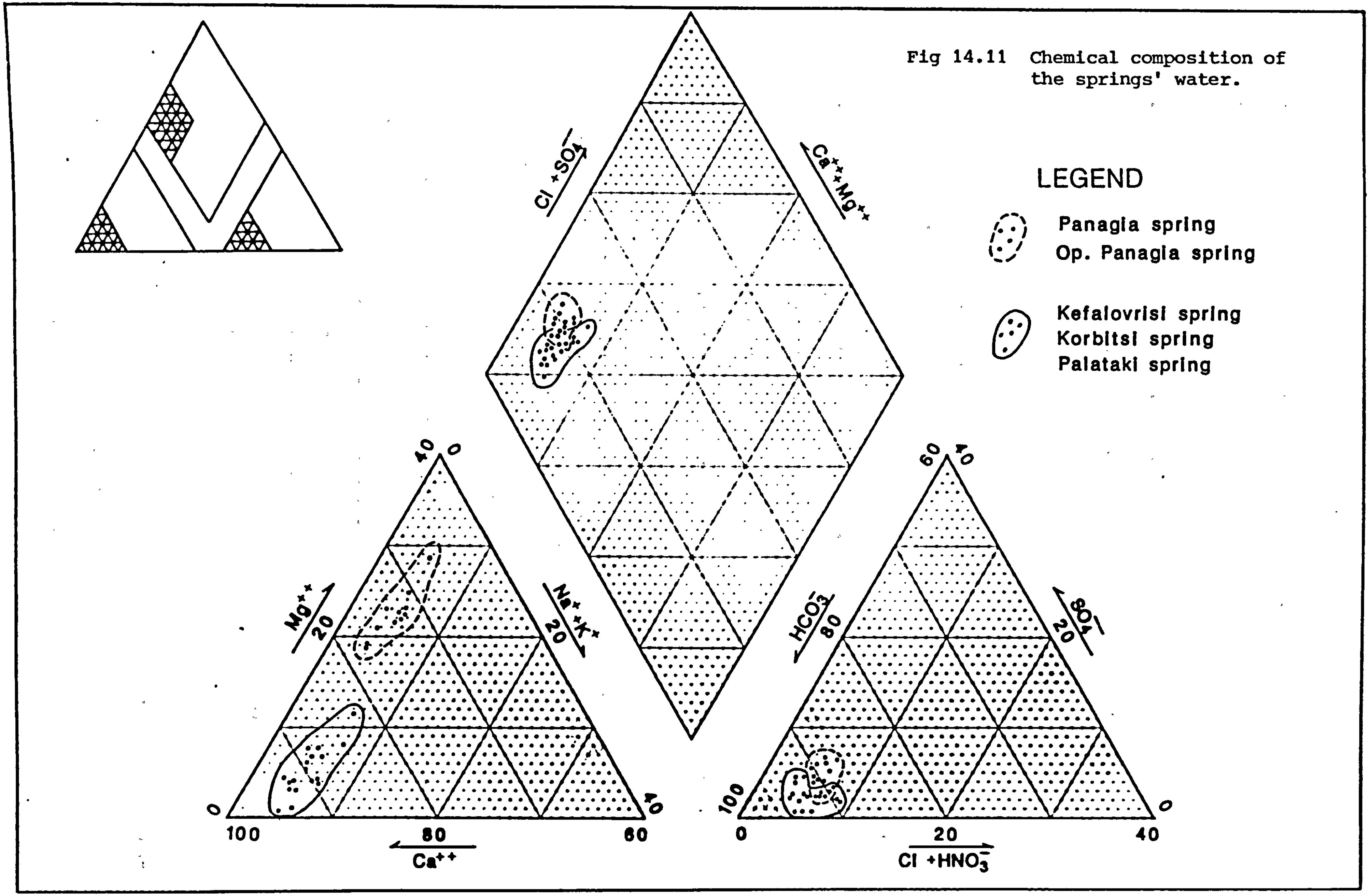


Fig 14.11 Chemical composition of the springs' water.

(approximately 400% higher) from the water chemistry of the aforementioned karstic springs.

As will be discussed later (Section 14.5), the chemical composition of the second group of springs strongly resembles the water chemistry of aquifer 1 and it is believed that these springs are related to it, perhaps being an overflow of this aquifer.

i) Karstic springs (1st group)

The Kefalovrisi, Korbitsi and Palataki springs belong to this group. They undoubtedly discharge the Upper Cretaceous limestones which outcrop on the northern side of the basin (Kefalovrisi and Korbitsi) or on its western side (Palataki), as is proved by careful evaluation of the hydrological evidence (Chapter 10 and Fig 9.1).

The mean ionic concentrations and mean hardness values for these springs are given in Table 14.6.

mgr/l										Hardness in $CaCO_3$ ppm		
Cations					Anions							
Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Total cations	Total anions	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Non permanent	Permanent	Total
1. 71	2.1	4.6	0.4	78.1	234	220	8.2	4.3	1.2	180	6	186
2. 94	3.4	4.1	0.4	102	306	293	7.1	3.4	2.5	240	8	248
3. 90	4.5	6	0.4	101	292	284	7.8	10.1	0	233	10	243

Table 14.6 Chemical composition and hardness values (mean values) of the springs: 1. Kefalovrisi (1982-84), 2. Korbitsi (1984) and 3. Palataki (1984).

It can be seen that the Kefalovrisi spring differs significantly from the others, mainly in the amount of calcium bicarbonate in solution which, in turn, affects the TDI content. This difference can also be

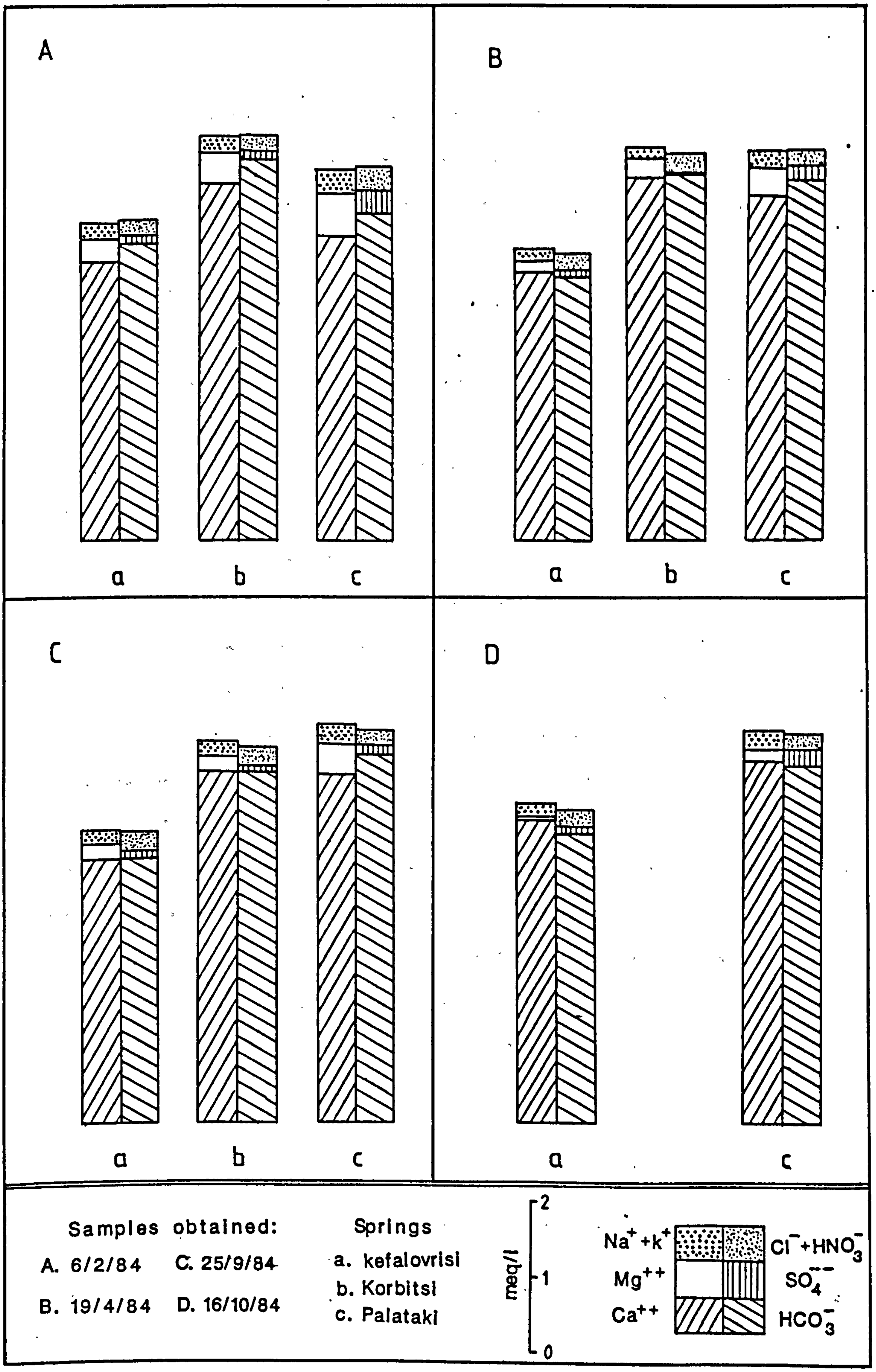


Fig 14.12 Chemical composition of samples from the springs.

noticed in the non-permanent (carbonate) hardness values and, of course, in the total hardness values for these springs.

The Kefalovrisi spring, which has the highest discharge of all the springs in the area, is seen to have the lowest calcium bicarbonate content and hardness values within the waters, both surface and groundwater, of the area.

The pH values of the spring water are 7.60 for Kefalovrisi and 7.40 for Korbitsi and Palataki, these reflecting the hydrogeological conditions of the springs and the fact that the Kefalovrisi water is less saturated with calcium.

It has already been stated (see Section 10.5.3) that the Kefalovrisi and Korbitsi springs are different discharge points of the same aquifer which is developed in the Upper Cretaceous limestones on the northern side of the basin. The differences noticed in the chemical composition of their water may possibly be due to the different hydrological features these two springs exhibit. The Korbitsi spring, for example, doubles its discharge during the wet season, while the Kefalovrisi spring has a summer discharge twenty times higher than that in winter. However, the most important factor affecting the water chemistry of these two springs is that the Kefalovrisi spring is an overflow-type spring, discharging an unconfined aquifer, while the Korbitsi spring discharges a partially confined aquifer with the water flowing towards and passing underneath the basin sediment.

The Ca^{++}/Mg^{++} ratio is generally very high, ranging between 34 (Kefalovrisi) and 20 (Palataki) (expressed in mgr/l) or between 21 and 12 (in meq/l) respectively, indicating that the movement takes place through an almost pure calcite (limestone) environment, while the HCO_3^{-}/SO_4^{--}

ratio ranges between 40 and 22 (in meq/l) respectively or 51 and 22 (in mgr/l). These ratio values are much higher than for any other water type found in the area.

In all these springs, small seasonal variations, which only represent a small percentage of the mean value of the major constituents and the TDI content, are observed. Almost no variation is noticed in the chemical composition, in contrast to the considerable variations they exhibit in discharge conditions (Fig 14.12). The same is true for their hardness values which, according to Shuster and White (1971), are an indication of a diffuse type of spring. According to them, springs of this type are, generally, near to saturation point.

Ineson and Langmuir (1974) pointed out that the diffuse-type feeder system springs have a higher total of dissolved solids (TDS) and show less variation in solute amounts and discharge.

ii) Panagia spring (2nd group)

The Panagia spring, together with the Opiste Panagia spring, both of which emerge at the contact of an outcrop of limestone with the superficial basin sediments and the 'first flysch' sediment, are the closest springs to the Kyparissia field.

These two springs, as already discussed in Section 10.5.4, show a hydrological relationship with the karstic aquifers developed in the Kyparissia field. The hydrochemical investigation (Section 14.5) confirms this and also identifies a close relationship between these springs and aquifer 1.

The mean values of the ionic concentration and the hardness values of the Panagia spring determined by the chemical analyses made in 1982-83 are given in Table 14.7.

mgr/l										Hardness in $CaCO_3$ ppm		
Cations					Anions							
Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Total cations	Total anions	HCO_3^-	Cl^-	SO_4	NO_3^-	Non permanent	Permanent	Total
69	13.1	4.8	0.4	87.3	282	261	8.9	10.6	1.2	214	12	226

Table 14.7 Panagia spring (mean values of ionic concentration and hardness, 1982-85).

Even given the predominance of calcium in the Panagia spring, the magnesium content accounts for a significant part of the total percentage (22%) of the cationic concentration, when amounts expressed in meq/l, which causes the water chemistry of this spring to differ greatly from that of the other springs, in which a lower calcium percentage (5.5%) is detected (Table 14.5, Fig 14.11).

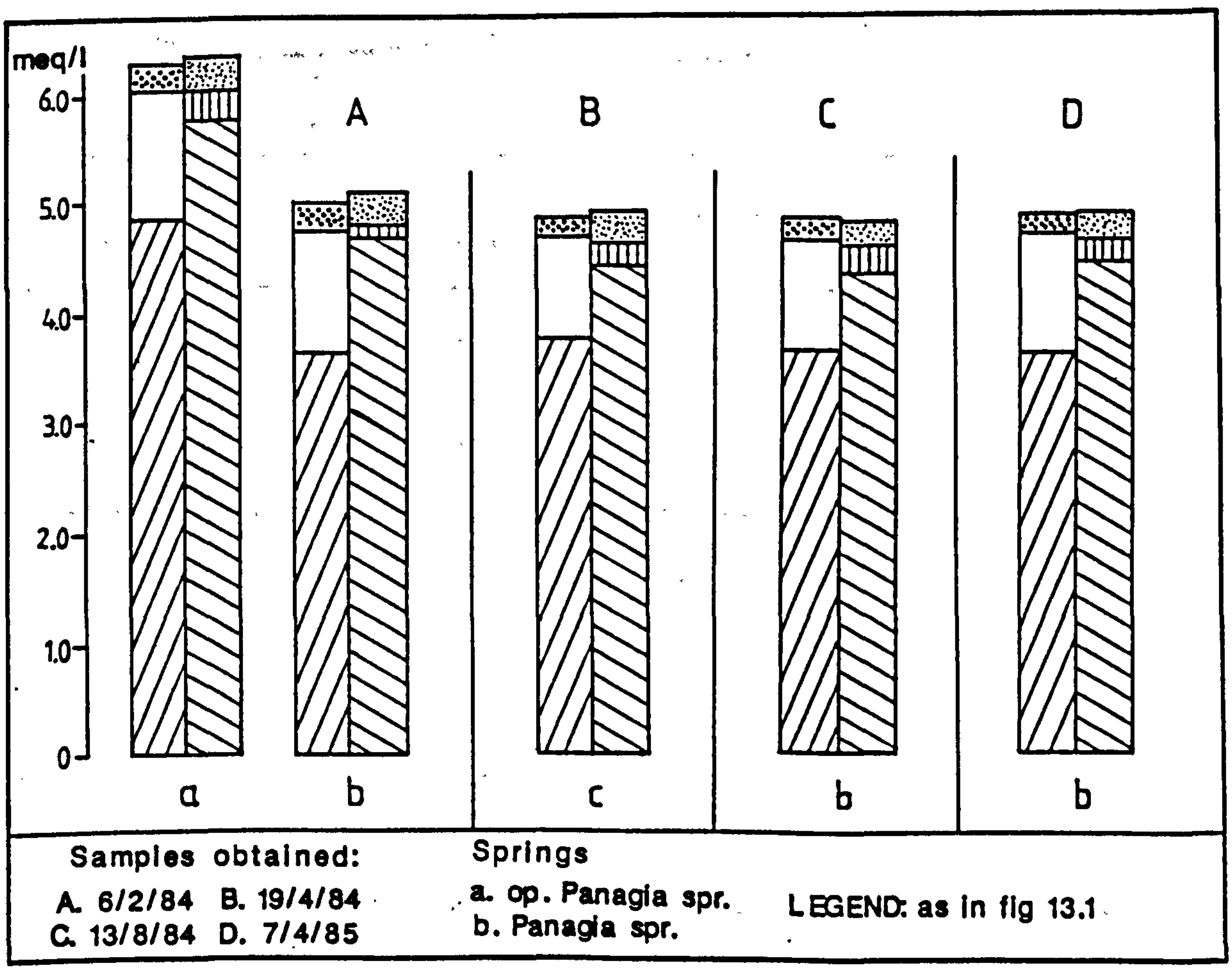


Fig 14.13 Chemical composition of water samples obtained from the Panagia and Opiste Panagia springs.

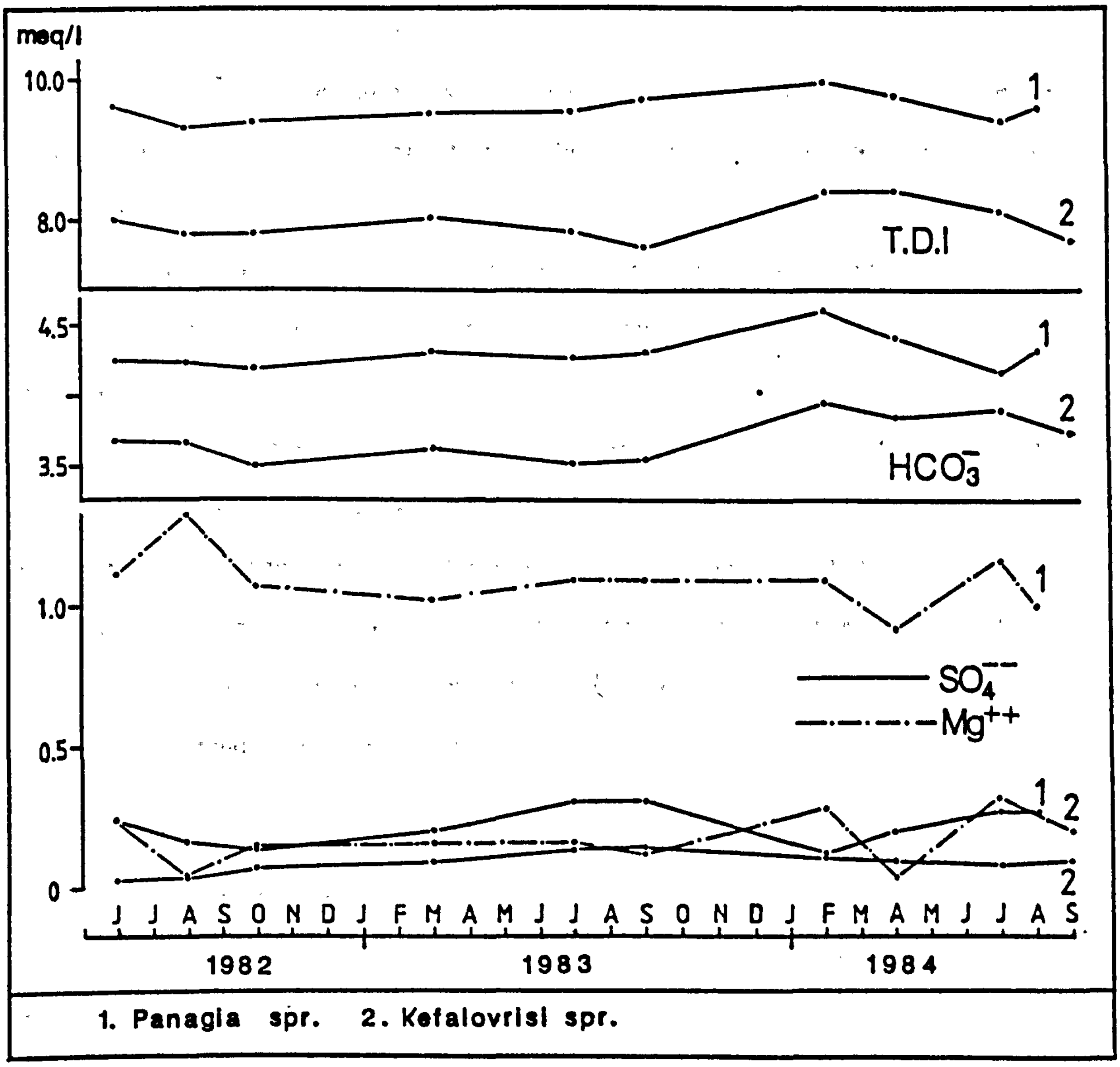


Fig 14.14 Variations in the quality of the spring water with time.

Here, the higher magnesium content is associated with a greater permanent hardness, which for this spring has a mean value of 214 ppm (as $CaCO_3$) and which is also reflected in the total hardness value, being on average 226 ppm (as $CaCO_3$).

The pH values measured averaged around 7.55 with a minimum of 7.30 and a maximum of 7.70. Generally, small variations in the pH values were observed.

The Ca^{++}/Mg^{++} ratio for the Panagia spring is 3.41 (expressed in meq/l) or 5.26 (in mgr/l), a value greatly different from that of the other springs and closely resembling that of aquifer 1 (Table 14.10). The HCO_3^-/SO_4^{--} ratio here is 0.25 or 20.7, expressed in meq/l or mgr/l respectively. The TDI content for the Panagia spring averages 370 mgr/l (9.63 meq/l).

The seasonal variations noticed in the chemical composition of the water of this spring also account here for a small portion of the mean values (Fig 14.13).

To make a comparison between the Panagia spring and the Kefalovrisi karstic spring, the values of the individual major ions and the TDI content during the time of the present study were plotted in Fig 14.14. From this figure, it can be observed that the Panagia spring exhibits constantly higher ionic concentrations (especially of the Mg^{++} ion) and TDI content than does the Kefalovrisi spring.

14.3 Alfios river hydrochemistry

The Alfios river was thoroughly studied for chemical characteristics. Samples were taken and analysed four times during 1984 from three different sites along its course through the Kyparissia field (Fig 13.1).

The Alfios river (see Section 8.1) drains the wider area of the basin of Megalopolis, the basin of Assea and a few other smaller basins before it leaves the Megalopolis basin. During the wet season, it receives the greater portion of its flow from direct surface run-off while, during the dry season, it is fed from a few karstic springs emanating from individual masses of Upper Cretaceous limestones further to the south of the basin, although a major component of its base-flow is received from water stored in the terrace gravel-bodies and partly from the overflow of the karstic aquifers developed in the vicinity of the Kyparissia field.

It is noticed that, during some summers, the Alfios river dries up south of the Kyparissia bridge. In such cases, the flow here takes place through the river bed gravels.

It is to be expected, in view of the above factors, that there should be a seasonal and also an areal variability in the chemical composition of the Alfios river water. These variations become evident by plotting the results of the chemical analyses of the samples on Piper diagrams (Figs 14.15 and 16) or by representing them in the form of bar graphs (Fig 14.17). In the Piper diagrams, only variations in chemical composition (percentages) of the anionic constituents are observed, which is the striking feature of the river water chemistry, as the cations composition (in percentages) shows almost no variation. From the bar graphs, the variations in the absolute values of the individual ionic concentrations and also in the TDI content can be observed.

Although the three samples were taken within short distances of each other (less than 2 km, see Fig 13.1 for location) along the river's course, areal variations in the water chemistry were observed. The greater variations, both in the ionic concentrations and in the TDI content, were noticed during the dry season (Fig 13.18) while, during the wet season, they were much smaller or even negligible.

Downstream, the concentration of most of the ions, and consequently also the TDI content, decrease, with the exception of the HCO_3^- anion for which an increase is observed.

These areal variations in the chemistry of the Alfios river water are believed to be due to local factors, mainly to the contribution from other water sources with a different (lower) chemical composition from the river's flow, especially during its low base-flow (dry season) in this area. Such sources are the bank storage water which emerges here and the overflow of the karstic aquifers developed in the vicinity of the

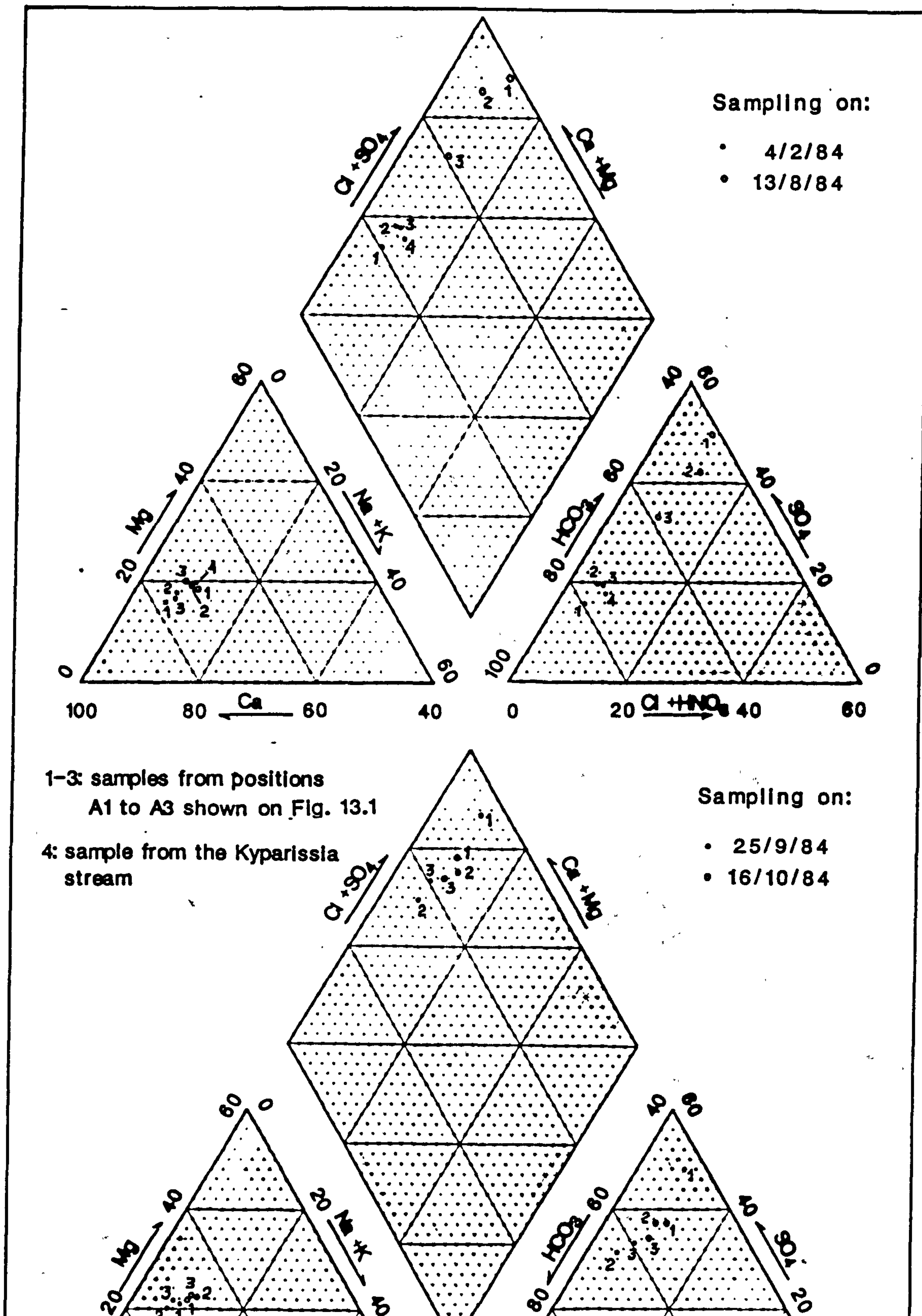


Fig 14.16 Chemical composition of the Alfios river water.

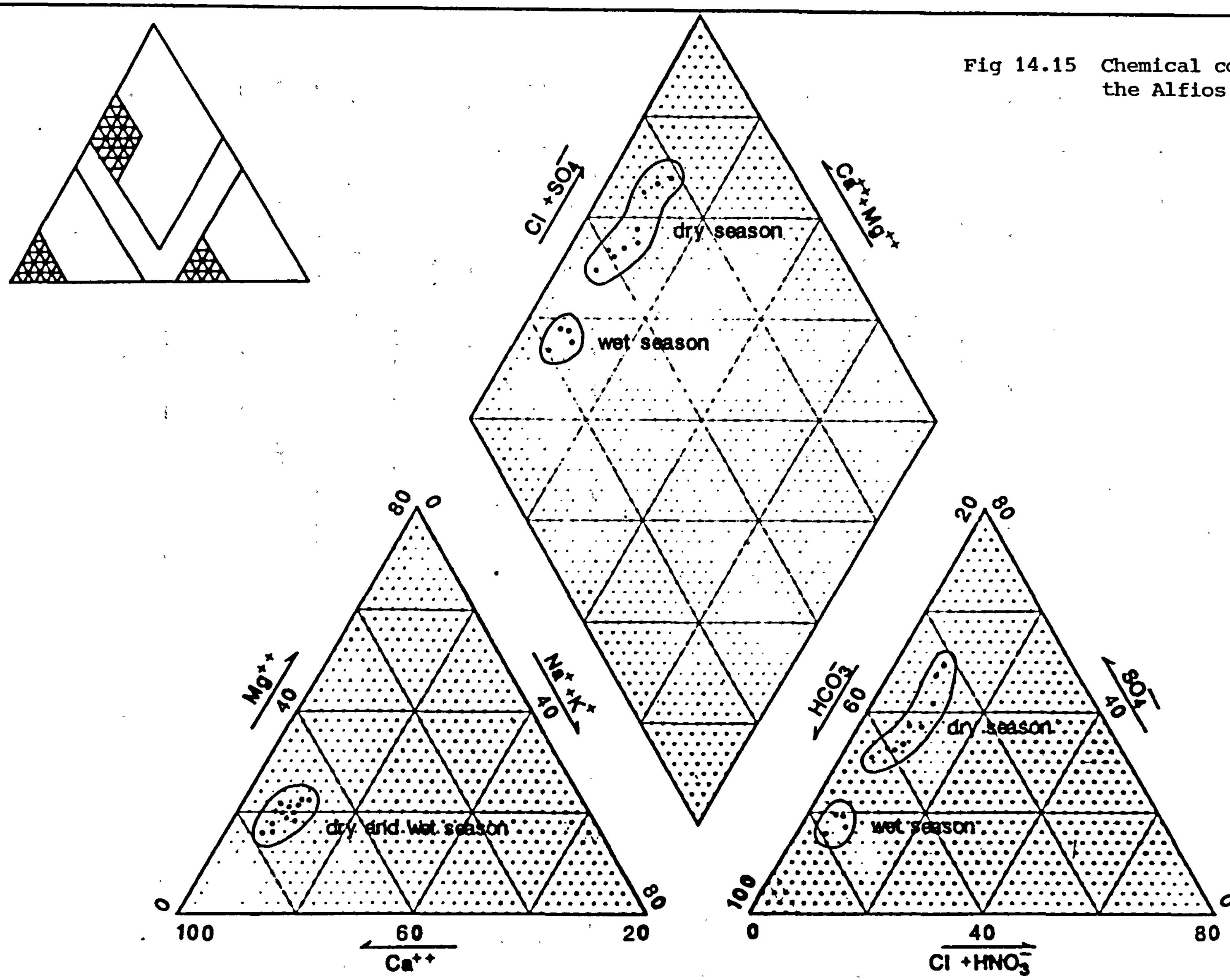


Fig 14.15 Chemical composition of the Alfios river water.

Kyparissia field. It has been pointed out that, during some summers, the river dries up upstream, as do the springs discharging these karstic aquifers, such as the small spring situated at the eastern pillar of the Kyparissia bridge, the intermittent spring of Aghia Sotira, which did not discharge at all in 1984, and sometimes also the Panagia and the Opiste Panagia springs.

Greater variations in the river water chemistry are also present on a yearly basis. These seasonal variations in the TDI content and in the ionic concentration are extremely high (Table 14.8, Fig 14.18).

The samples taken on 4 February 1984 are considered to be representative of the wet season, during which the Alfios river has a high rate of discharge, with the water originating from direct run-off and discharge from karstic springs. All the other sets of samples were taken during the dry season - as, until the end of October 1984, significant rainfall had not taken place - when the Alfios river has a low rate of discharge.

1984	mgr/l Cations						Anions				Hardness in $CaCO_3$ ppm		
	Ca^{2+}	Mg^{2+}	Na^+	K^+	Total cations	Total anions	HCO_3^-	Cl^-	SO_4	NO_3^-	Non permanent	Permanent	Total
4/2	78	10.6	8.7	0.8	98	296	240	9.9	46	0	197	40	237
13/8	103	16.8	13.8	2.3	136	390	212	17.7	145	14.9	174	151	325
25/9	91	15.4	9.4	1.6	117	337	210	12.8	112	2.5	172	118	290
16/10	67	13.1	10.6	1.2	92	268	164	12.4	85	6.8	131	131	262

Table 14.8 Chemical composition and hardness values of the Alfios river water (mean values of the samples obtained during 1984).

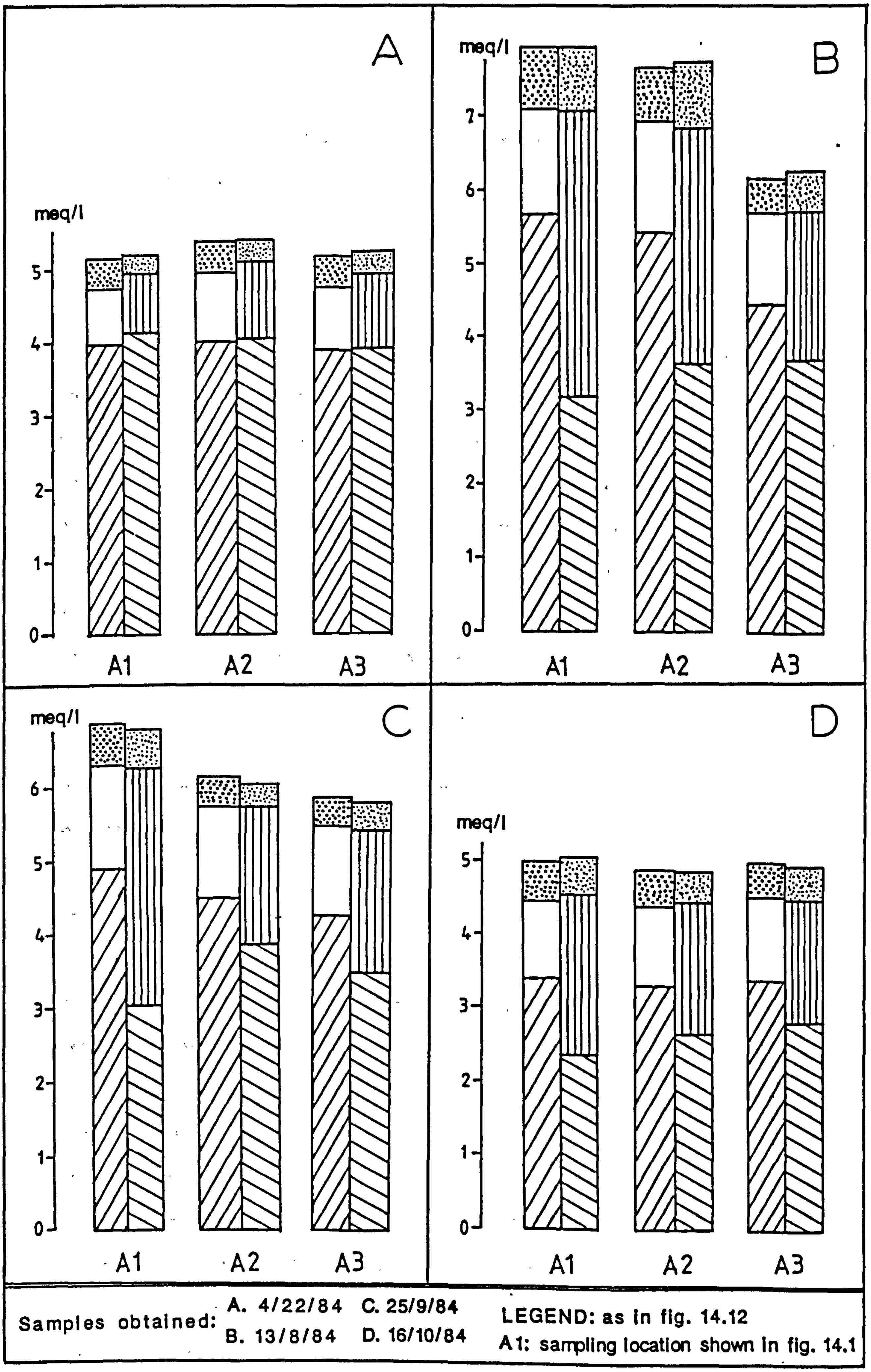


Fig 14.17 Chemical composition of the Alfios river water.

As can be seen in Table 14.8, the samples obtained on 13 August 1984 have higher TDI content and ionic concentrations, with the exception of HCO_3^-, than any of the others.

The TDI content is increased in these sets of samples (4 February and 13 August) by, on average, about 35%. Within the cations, the K^+ concentration shows a high increase of 187%, while the Mg^{++} and Na^+ ions are increased by 58% and the Ca^{++} ion, which is also the predominant cation here, by 32%. Within the anions, the SO_4^{--} ion shows an extreme increase of 215% and the Cl^- increases by 79%, while the HCO_3^- ion, which is the predominant one, is, on the contrary, decreased by 22% on average. In addition, the NO_3^- concentration, which is practically zero during the wet season, reaches an average value of 14.9 mgr/l, or 21.7 mgr/l in the sample from sampling position A2 (much lower than the World Health Organisation limit of 45 mgr/l as NO_3^-).

There is a striking increase in the SO_4^{--} concentration (215%) which, in the sample taken from sampling position A1 on the 13 August, reaches a value of 184 mgr/l.

During the dry season (13 August to 16 October), there was a considerable, almost progressive decrease in the ionic concentrations, TDI content and hardness values in each set of samples. In fact, the calcium bicarbonate concentrations in the last set of samples have values even lower than those during the wet season.

These seasonal variations observed in the Alfios river water chemistry may be attributed to the local factors referred to above and also to seasonal factors such as:

1) various contributions of water with different chemical composition to the river's flow from other sources (ie direct run-off, base flow) during the year;
2) different rates of discharge during the year;

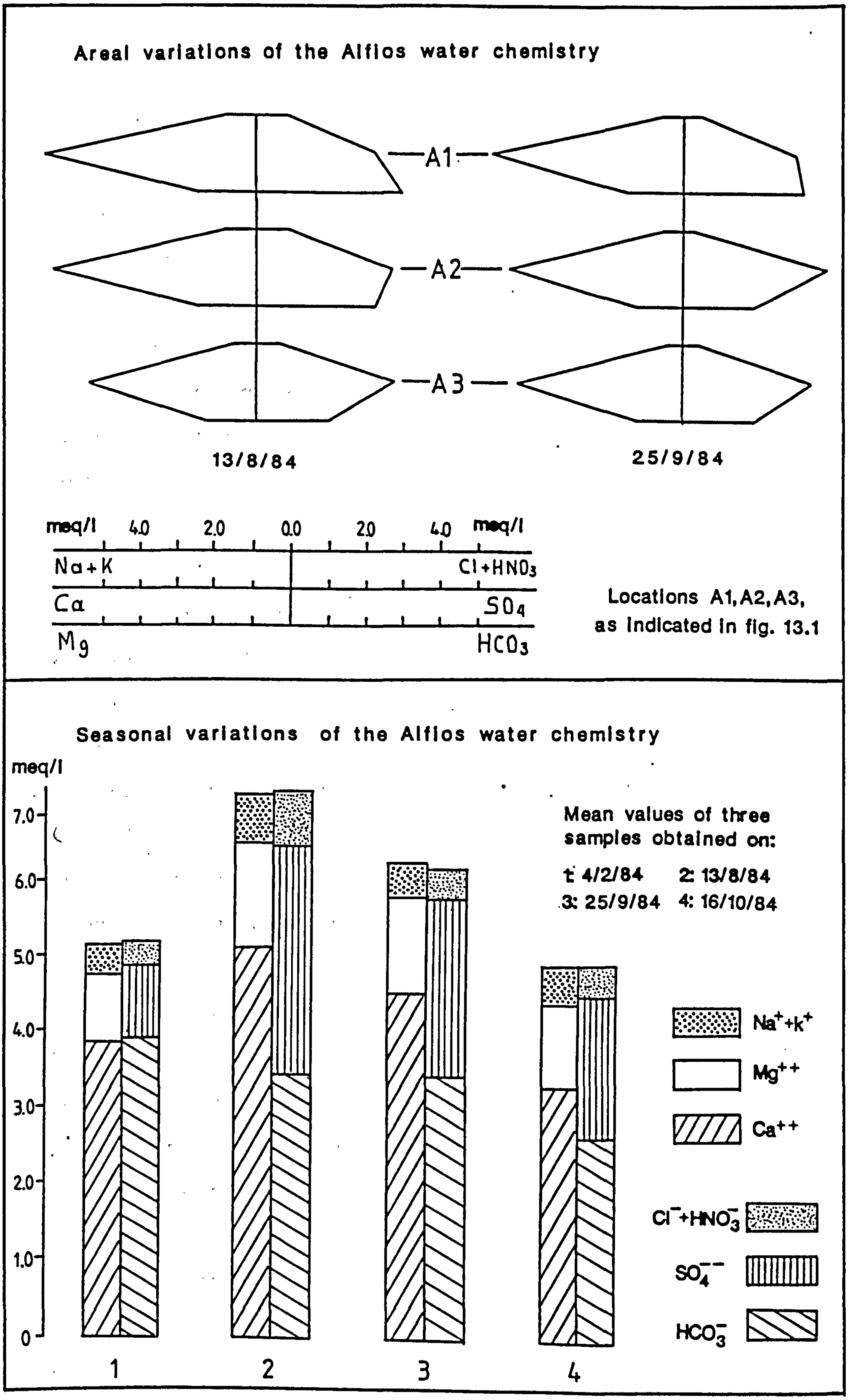


Fig 14.18 Variations in the Alfios water chemistry.

3) changes in water temperature influencing the ionic concentrations.

The Alfios river water is of Ca/Mg:HCO_3/SO_4 type and, in a few samples, of Ca/Mg:SO_4/HCO_3 type.

The high SO_4^{--} content in the river is reflected in the permanent hardness values, which range, on average, between 40 (wet season) and 151 (dry season) ppm (as $CaCO_3$), while the generally low bicarbonate content causes the non-permanent hardness values to be rather low, especially during the dry season. In general, the Alfios river water has, on average, the highest total hardness values within the waters present in the area.

The Ca^{++}/Mg^{++} ratio in the Alfios river water shows a lower value than the water from the aquifers and spring water. It ranges between 7.3 (wet season) and 5.1 (dry season) (amounts expressed in mgr/l). The Ca^{++}/Mg^{++} ratio decreases gradually throughout the year but it generally varies within narrow limits. The HCO_3^{-}/SO_4^{--} ratio, on the other hand, has a much greater value during the wet season (5.2) than during the dry season (1.7 on average) (amounts in mgr/l). Values, especially those during the dry season, are much lower than those in all other waters present in the area, due to the high SO_4^{--} content in the Alfios river water.

The Alfios river water has no apparent carbonate alkalinity and its pH fluctuates between 7.40 and 8.10 (with an average of 7.80), as it contains an appreciable amount of calcium. Only one sample was found with a pH of 8.40 as a result of CO_3^{--} anions in solution. A higher pH value is generally noticed during the wet season due to the higher bicarbonate content in solution (as carbonic acid).

Finally, the sample of water taken from the Kyparissia riverlet on 4 February exhibits the same chemical composition (with regard to percentages of ions present) as the sample taken from the Alfios river at the same time, although the absolute values of the ionic concentrations, the TDI content and the hardness values were found to be much lower.

14.4 Hydrochemistry of the clastic aquifers

As mentioned in Chapter 11.3, there are a few small independent aquifers developed within the basin sediments of the Kyparissia field. There are also superficial aquifers developed in the terraces along the Alfios river, which contribute a large amount of water to the Alfios river flow, especially during the dry season. During a few summers, its flow takes place through the recent gravel-bodies to the south of the bridge at Kyparissia.

Unfortunately, no samples were taken from these two different types of aquifers, as neither wells nor shallow boreholes were dug into them. Of the springs which are overflows of the terrace aquifers, that at Aghia Sotira did not flow at all during the sampling period (1984), while the small one situated next to the eastern pillar of the Kyparissia bridge was sampled only once (4 February).

Only a few data are available, taken from the Otto Gold study (1961-63), relating to the water chemistry of the terrace aquifers and to the small, independent shallow aquifers developed in the basin sediments.

According to these data, the water of the small water bodies developed in the basin sediments, which in some cases are under confined conditions (artesian flow) and in other cases discharge through small springs, differs greatly from the other surface and groundwaters of the area. The water samples taken from them are characterised by extremely high total hardness values, ranging from 520 up to 1000 ppm (as $CaCO_3$), while one value as high as 1800 was reported. These very high values are due to the high permanent hardness (415-790 ppm as $CaCO_3$), while the temporary hardness ranges within the usual limits of the other water sources in the area.

The sulphate and chloride ionic concentrations reported were also very high and are responsible for the high permanent hardness values. The sulphate concentrations measured ranged from 5.6 to 700(?) mgr/l and the chloride concentrations from 35 to 180 mgr/l. The calcium, and especially the magnesium contents, were also high. For the Ca^{++} concentration, values from 120 to 310 mgr/l were reported and for Mg^{++}, values from 45 to 80 mgr/l.

It is also stated in this report that, in most cases, the water of the small water bodies has a higher temperature than the annual average temperature (14°C) and this is attributed to the oxidisation processes within the lignite beds.

A considerable amount of water flows through the gravel bodies of the terraces - mainly the Lower and the Middle terraces - especially during the dry season while, when the Alfios river dries up south of the Kyparissia bridge (as during 1962), the total flow takes place through these bodies.

The water of these aquifers, according to the data in the report, presents a similar chemical character to the water of the Alfios river and to the tributaries (eg Elisson) by which it is fed.

The water of the samples taken from the recent gravel body or from wells dug into the Middle terrace, to the north of the village of Thoknia, shows, as does the river water, both seasonal and areal variations. In general, the ionic concentrations of the major constituents and also the hardness values appear to be slightly higher than those of the river water for the corresponding time of the year, although the data available are not adequate for sufficient correlations to be carried out to confirm this. The temperature follows, with smoother values, the seasonal temperature curve. During summer, it is slightly cooler while, during winter, it is slightly warmer than the Alfios river water.

The data given by the Gold Report (1963) on the small spring situated next to the pillar of the Kyparissia bridge and the intermittent spring of Aghia Sotira, situated 100 m to the west, both of which, as previously noted, consist of an overflow of the water flowing through the terraces (mainly, the Lower and the Thoknia ones), show for these springs a similar water character (Table 14.9) to that of the Alfios river (Table 14.15) but with generally greater ionic concentrations.

	mgr/l										Hardness in $CaCO_3$ ppm		
	Cations					Anions							
	Ca^{2+}	Mg^{2+}	Na^+	K^+	Total cations	Total anions	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Non permanent	Permanent	Total
1.	81	14.3	6.1	0.4	102	315	286	12.1	11.3	5.2	229	32	261
2.	72	21(?)	-	-	-	-	-	14.9	11.4	-	239	31	270

Table 14.9 Spring water chemistry and hardness (from Gold Report, 1963).
1. Spring at Kyparissia bridge (sample taken on 16 January 1963).
2. Aghia Sotira spring (sample taken on 2 March 1963).

14.5 Correlations between the various water types

So far, the occurrence and mainly the chemical composition of the different water types present in the area - aquifers, karstic springs, springs and surface water - have been studied.

In this Section, comparisons and correlations between them will be examined, in order to elucidate any existing relationships between them and in an attempt to determine the origin of the groundwater of the Kyparissia field aquifer. Then, after a hydrochemical relationship has been established, the probable mechanisms by which the aquifer waters obtain their chemical composition will be sought.

The average chemical composition of the water of the Alfios river, the aquifers, the springs and the karstic springs is given in Table 14.10. The chemical composition for the Alfios river water is given, both for the wet season (4 February 1984) and for the dry season (mean of 13 August, 25 September and 16 October 1984), since these two differ greatly.

On the basis of this table, the various natural waters present in the area can be divided into two groups, mainly according to the Mg^{++} content, but also to the contribution of the SO_4^{--} ion to the ionic concentrations.

The first group is made up of the Alfios river, both karstic aquifers (1 and 2) and the Panagia spring. The water from all these sources has a high Mg^{++} content, ranging from 10 to 14 mgr/l. The second group, on the other hand, which includes the Korbitsi and the Kefalovrisi springs issuing from limestone masses to the northern side of the basin, presents a much lower level of Mg^{++} content, ranging here from 2 to 3 mgr/l.

As for the SO_4^{--} ion contribution to the chemical composition of the various waters, it can be clearly seen that the first group has a higher content (10-115 mgr/l) than the karstic springs (less than 4 mgr/l).

Aquifers 1 and 2 and the Panagia spring have common characteristics and must, therefore, be associated with the Alfios river water, rather than with water from the karstic springs of Kefalovrisi and Korbitsi.

This grouping of the various water types is also evident from the plot of their chemical composition on the Piper diagram (Fig 14.19).

Table 14.11 gives the various ratios between the ionic concentrations and the TDI content in the waters present in the area while, in Fig 14.20, which is a graphical representation of the Ca^{++}/Mg^{++}

		meq/l										Hardness in $CaCO_3$ ppm		
		Cations					Anions							
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Total cations	Total anions	HCO_3^-	Cl^-	SO_4^{--}	NO_3^-	Non permanent	Permanent	Total
Alfios river	dry season	4.33	1.24	0.49	0.04	6.10	6.10	3.20	0.40	2.37	0.13	119	159	278
	wet season	3.87	0.87	0.38	0.02	5.14	5.18	3.93	0.28	0.96	0.00	40	197	237
Aquifer 1	subzone A	3.86	1.17	0.23	0.02	5.28	5.30	4.61	0.30	0.31	0.08	21	231	252
	subzone B	2.86	1.10	0.16	0.01	4.13	4.12	3.67	0.20	0.25	0.00	14	184	198
Aquifer 2		4.59	0.84	0.38	0.02	5.83	5.84	4.35	0.35	1.08	0.06	54	218	272
Panagia spring		3.55	1.04	0.21	0.01	4.81	4.82	4.35	0.25	0.21	0.01	12	218	230
Korbitsi spring		4.69	0.28	0.18	0.01	5.16	5.12	4.81	0.20	0.07	0.04	8	240	248
Kefalovrisi spring		3.61	0.20	0.19	0.01	4.01	4.00	3.66	0.24	0.09	0.01	7	183	190

Table 14.10 Chemical composition of the natural waters of the Kyparissia field (mean values of the samples obtained during 1984).

and HCO_3^-/SO_4^{--} epm ratios, the results of all the chemical analyses carried out during the present study are plotted. In this Figure (14.20) it can be seen that the karstic springs, represented by areas a and c, depart greatly, concerning the Ca^{++}/Mg^{++} ratio, from all other water sources, which plot almost on the same line. In the HCO_3^-/SO_4^{--} section of the figure, however, this separation is not evident due to the generally very high ratio values, with the exception of those for the Alfios river and for aquifer 2. This difference is also clearly shown numerically in Table 14.11.

meq/l TDI: cations & anions		Ca^{++}/Mg^{++}	Ca^{++}/TDI	Mg^{++}/TDI	HCO_3^-/SO_4^{--}	HCO_3^-/TDI	SO_4^{--}/TDI
Alfios river	dry season	3.49	0.35	0.102	1.35	0.26	0.194
	wet season	4.45	0.37	0.084	4.09	0.38	0.093
Aquifer 1	subzone A	3.29	0.36	0.110	14.87	0.44	0.029
	subzone B	2.60	0.35	0.133	14.68	0.45	0.030
Aquifer 2		5.46	0.39	0.072	4.03	0.37	0.092
Panagia spring		3.41	0.37	0.108	20.71	0.45	0.022
Korbitsi spring		16.75	0.46	0.027	68.71	0.46	0.007
Kefalovrisi spring		18.05	0.45	0.025	40.67	0.46	0.011

Table 14.11 Epm ratios of the ionic concentrations in the various waters of the Kyparissia field.

Two sub-groups can be further distinguished within the first group, on the basis of their SO_4^{--} content (Tables 13.10 and 11). Thus, water from aquifer 2, which (in absolute values) tends to resemble the Alfios

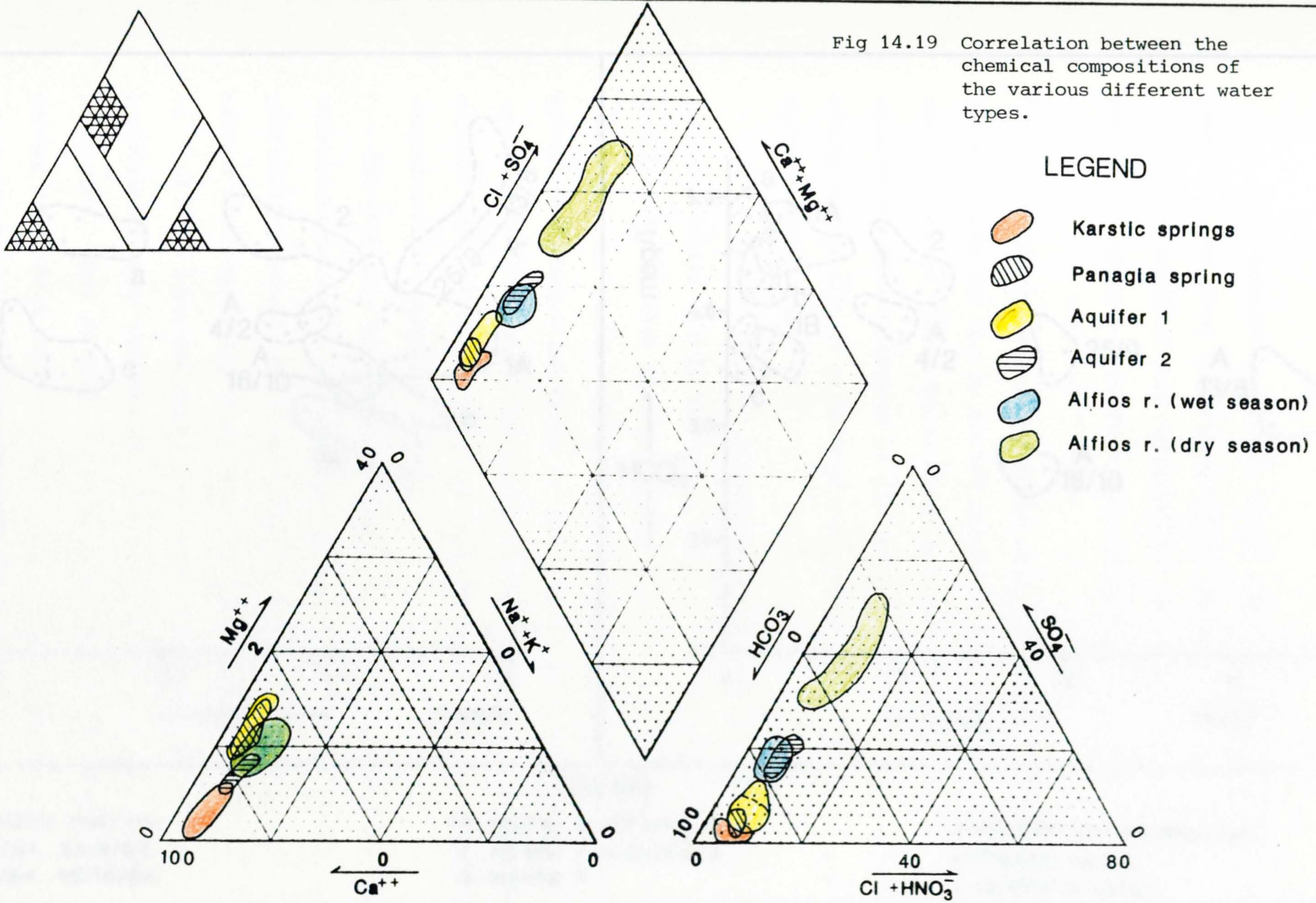


Fig 14.19 Correlation between the chemical compositions of the various different water types.

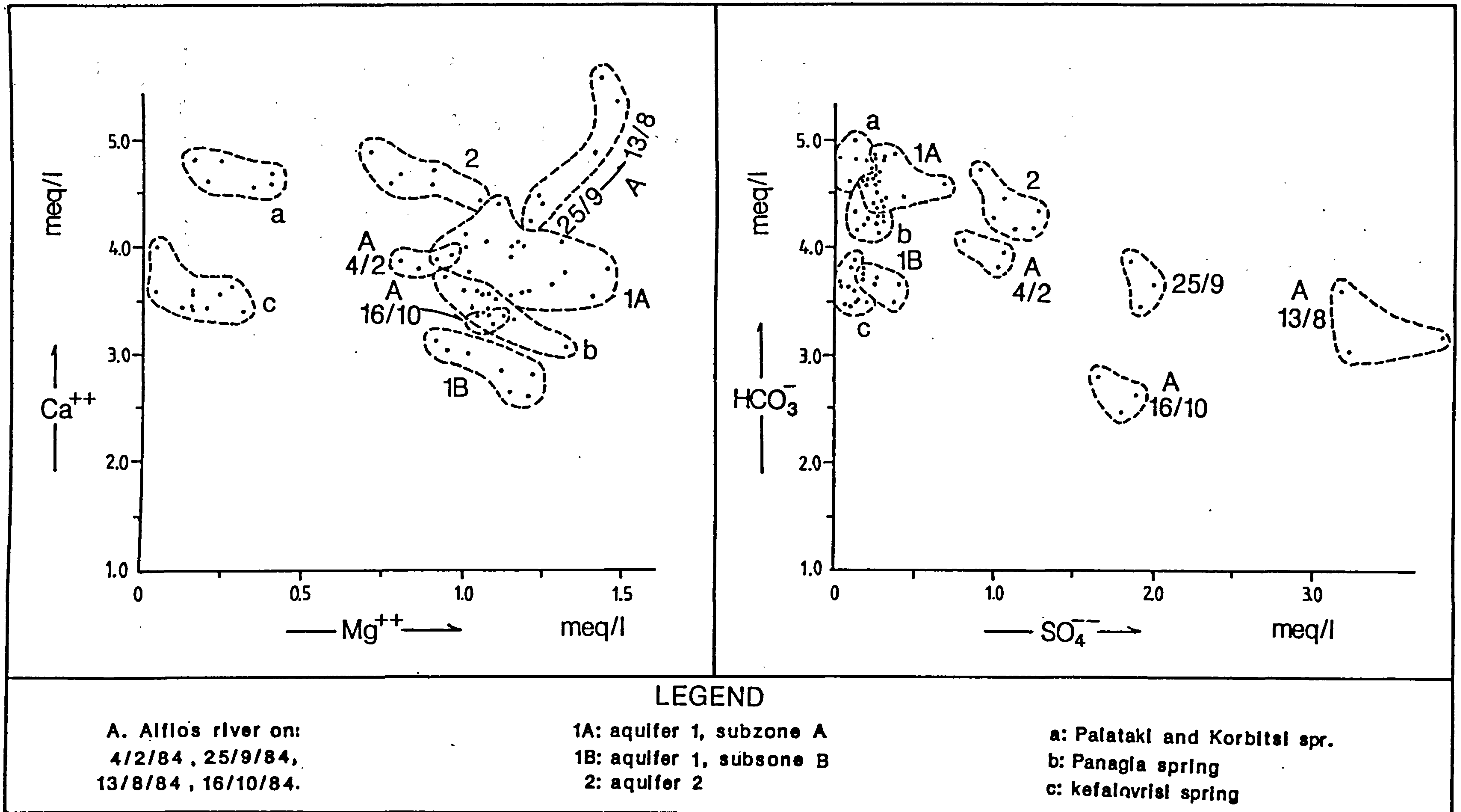


Fig 14.20 Ca^{++}/Mg^{++} and $HCO3^{-}/SO_4^{2-}$ content of the Alfios, aquifers and springs.

river water, demonstrates a much higher sulphate content than aquifer 1 (subzones A and B) or the Panagia spring (Tables 14.1 and 14.5).

On the basis of this information, the Panagia and Opiste Panagia springs are believed to consist of an overflow of aquifer 1.

Great differences are sometimes observed in the concentrations of the other ions and also in the TDI content between the various members of the first group. These may be the result of a different hydrogeological relationship between them or of the physico-chemical or other processes acting individually or collectively to produce the evolution observed in their water chemistry.

It is evident from the hydrogeological research (Chapter 12) that aquifer 2 is fed only by the Alfios river. Due to its small extent and resultant small water storage capacity, it is evident that the water pumped from it, via the wells F6 and F7, comes directly from the Alfios river. The changes occurring in the Alfios river water entering the aquifer often for a short time, before being pumped via wells F6 and F7, will be used as a basis for an explanation of the water chemistry evolution within aquifer 1.

The chemistry of the water from aquifer 2 experiences only small seasonal variations in contrast to the Alfios river water. The water of this aquifer demonstrates a great decrease in the concentrations of the various ions, especially of the SO_4^{--} ion, but with the exception of the Ca^{++} and HCO_3^- ions, for which an increase is noticed, although it is not stoichiometrically sufficiently great to balance the decrease of the other ions. This is true of the water during the dry season, when it reaches its highest ionic concentrations. During winter, smaller changes occur, mainly a great increase in the calcium bicarbonate and a smaller increase in the other anions.

The great decrease in the SO_4^{--} ionic concentration during the dry season, when the SO_4^{--} ion contributes between 35 and 40% of the total anionic concentration of the Alfios river water, is accompanied by a correspondingly higher decrease in the Mg^{++} ion. Aquifer 2 contains the water with the lowest Mg^{++} content within aquifer groundwater in the area. This permits the conclusion to be drawn that a great proportion of the sulphates are in the form of $MgSO_4$. The relative decrease in the SO_4^{--} ion in the aquifer groundwater, compared to the river water, can be explained by the precipitation of the sulphates, shown by the decrease in TDI content.

Furthermore, the water from well F6, which is situated a little closer than is well F7 to the point at which the Alfios river water percolates down, always has higher Mg^{++}, Na^+, K^+, Cl^-, SO_4^{--} and TDI contents and a lesser concentration of Ca^{++} and HCO_3^- (Fig 14.10). The water from well F6 is more similar to the Alfios river water than is water drawn from well F7.

In the second sub-group, which comprises aquifer 1 and the Panagia and Opiste Panagia springs, it can be seen (Table 14.11, Fig 14.19) that all these sources contain water of similar chemical composition (regarding the contribution of the individual ions as percentages) to the Alfios river water and that all or part of their water must, therefore, originate from the Alfios river, although they differ greatly in respect of the absolute values of their ionic concentrations (Table 14.10).

A detailed study of the water samples from subzone A of aquifer 1 revealed small but always detectable differences in the groundwater samples taken from different wells (Figs 14.6 and 14.7), related to their position within this subzone in relation to the recharging area. The closer they are to it, the greater the ionic concentrations.

Another point that should be noted is that the seasonal variations in the aquifers' groundwater - accounting for only a small percentage of the mean value - were greater in aquifer 2 than in the subzone A, with subzone B showing the smallest degree of seasonal variation.

Changes in the chemistry of the Alfios river water similar to those taking place in aquifer 2 are noticed within subzone A. During the dry season, a great decline in the TDI content is observed. It is associated mainly with a decrease in the Ca^{++} and SO_4^{--} ions and, to a lesser extent, with the decrease of other ions, with the exception of HCO_3, for which a great increase is noticed. During the wet season, a great increase in the Mg^{++} and HCO_3^- ions occurs, while a great fall in the SO_4^{--} content and a slight fall in the Na^+ content are noticed.

A further decrease (about 20%) in all the ionic concentrations independently and, consequently, in TDI content in respect of subzone A is noticed as the water moves from subzone A to subzone B of aquifer 1. This indicates that the processes responsible for the changes observed in aquifers 2 and 1A had more time and distance over which to have effect and that further solids precipitated.

The Panagia spring discharges water with a slightly lower TDI content (8-10%) than subzone A, due to a decrease in all but one of the ions and higher by about 15% than subzone B, due to an increase in all the ions except SO_4^{--}, for which there is a further reduction.

The main reason for these changes exhibited by the Panagia spring water, and especially for the ionic rise in respect of subzone B, is that, quite apart from the processes taking place within aquifer 1 up to the spring, the spring water sampled had been freely discharged while the samples taken from the aquifer were from pumped wells.

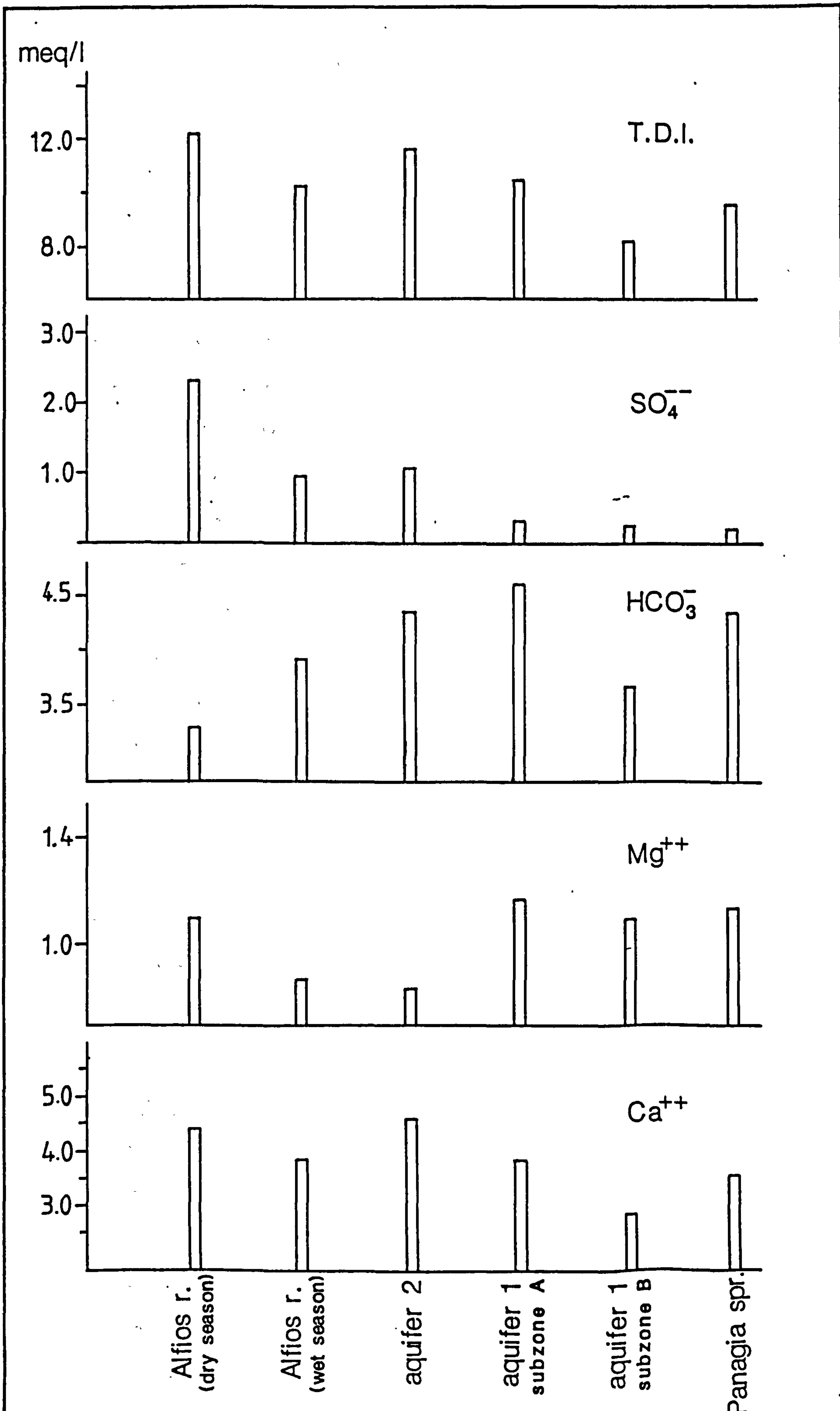


Fig 14.21 Ca^{++}, Mg^{++}, HCO3-, SO4-- and T.D.I. content of the Alfios, aquifers and Panagia spring (mean values)

The Opiste Panagia spring water has a much higher TDI content than the water of the Panagia spring, due to a highly increased concentration of calcium bicarbonate, which indicates that a supplementary source of free CO_2 exists here.

The water chemistry of the Alfios river, subzone A, subzone B and the Panagia spring, together with changes in the ionic concentrations, are represented in Fig 14.21.

The nature of the aquifers' groundwater suggests an interaction of the river water with the new hydrogeological environment.

However, the principal mechanisms and processes which could affect the evolved aquifer water chemistry in this case are the following:

i) Mineral solution effects and chemical solid state precipitation, due to changes in physico-chemical conditions eg pressure, partial pressure of the gases (CO_2), temperature, experienced by the water as it moves into the new environment.

ii) Mixing with water of different chemical composition.

iii) Filtration of the dissolved solids and suspended particles.

iv) Biochemical reactions.

Ion-exchange mechanisms may be discounted in the present case, for they constitute a principal process in the development of Na-rich waters, by replacement of the divalent Ca^{++} and Mg^{++} ions.

i) <u>Mineral solution</u>: The increase of the Ca^{++}, concurrent with HCO_3^-, must result from the solution of limestone in the presence of free CO_2. As the river water moves into the carbonate environment, it is to be expected, under the new physico-chemical conditions, that such a solution would take place if the water is undersaturated with Ca^{++}, ie contains free CO_2 or, most probably, if another source of surplus CO_2 exists.

ii) Precipitation of the sulphates and, to a lesser extent, of the chlorides, especially during the dry season, must occur as shown by the decrease in TDI content (Table 14.10).

These physico-chemical processes appear to play the most significant role in creating the differences in water chemistry between the Alfios river water and the aquifers and also within aquifer 1.

Analyses of pumping well samples showed them to be significantly oversaturated with Ca^{++} due to pressure reduction in the aquifer, as this causes a corresponding reduction in the partial pressure of CO_2 (Lawrence et al. 1976).

The equilibrium solubility of carbonates could be an important mechanism in controlling the concentration of ions where the water is undersaturated in respect of calcium bicarbonate.

The only evident difference in conditions between the Alfios river and the water in the aquifers, especially during summer when the greater changes are observed, is their temperature. Thus, as the river water moves into a cooler environment, the sudden change in temperature most probably provokes changes in the chemical composition, as the constant of mineral solubility is decreased and precipitation of chemical solids, which must be occurring, as shown by the TDI content, decreases. It is possible that the stable aquifer water temperature (approximately 14°C) could be responsible for the lack of variability in the chemical composition of the aquifer water identified.

iii) Mixing of water is a common hydrochemical process in the natural environment, although, as mixing takes place, it is usually accompanied by other processes and changes in independent variables, such as salinity, partial pressure of gases and temperature. It is thus difficult to obtain an ideal mixture. According to Wigley and Plummer (1976), the concentrations of the individual ions are often non-linear functions of their end-member values, especially for solutions containing carbonate species, due to their redistribution. For the latter, the conditions pertaining (ie closed or open to a CO_2 system, temperature) play a determinative role in the nature of the resultant mixture.

In order for the Alfios river water to be diluted and to acquire the same nature as the water in the aquifers, it would need to be mixed with water of a different chemical composition, specifically, a water with lower ionic abundances. This does not appear to take place here, as the only such source, ie the water from the limestones feeding the karstic springs of Kefalovrisi and Korbitsi, has already been discounted due to its low Mg^{++} content (Table 14.10) and the low Mg^{++} contribution to the total cationic constitution of their water (Table 14.11, Fig 14.20).

Furthermore, the water from aquifer 1 (subzone B), which must immediately become a member of the mixture between the Alfios river water and the karstic water, shows a lower TDI content (218 mgr/l), which is the lowest known value in the whole area and is lower than the value for the karstic water discharging from the Kefalovrisi and the Korbitsi springs, with a TDI content of 312 mgr/l and 408 mgr/l respectively, this karstic water supposedly being the end result of the mixing of waters.

iv) Filtration of the dissolved constituents and of the suspended small particles such as lignite particles takes place mainly in the water which moves through the gravel bodies and later percolates down to the aquifers and, to a lesser extent, within the aquifer, due to the type of water circulation, ie taking place predominantly through open channels.

v) Biochemical reactions could be restricted to the reduction of sulphates by anaerobic bacteria, resulting in the production of H_2S and CO_2. Carbon dioxide released as a by-product of this process increases the bicarbonate ions in solution, this increase being related to the fall in the sulphate content (Downing, 1967). The increase in carbonates is not, however, stoichiometrically equivalent to the decline in sulphate during summer, either because the carbonate formed is precipitated under the physico-chemical conditions existing in the aquifer or, more probably, because some of the sulphates precipitate as water enters the aquifer.

It can be tentatively concluded, therefore, that:

1) The water of the Panagia and the Opiste Panagia springs resembles the water of aquifer 1 and must consist of overflows from this aquifer.

2) The further from the Alfios river the discharging point is located, the greater the decline in the ionic abundances in the water of the aquifer. Thus, the relative ionic abundances - either as TDI content or individually (except Mg^{++} in aquifer 2) - are: aquifer 2 > subzone A > subzone B. These differences also occur within the aquifers, as is shown by the chemical composition of water taken from wells sunk at different points in the aquifers.

3) The aquifer water originates exclusively from the Alfios river and gravel bodies, as mixing with karstic water from the limestones outcropping to the north-eastern side of the basin was discounted as a possible source.

4) Although the processes responsible for the changes observed in the Alfios river water moving into the aquifers cannot be clearly established, it appears that physico-chemical processes, such as mineral solution (eg of $CaCO_3$) and chemical precipitation are of major importance, while the biochemical reduction in sulphate could also contribute to the changes observed.

14.6 Variation of water quality with time

Relatively few chemical analyses of the water in the study area have been included in previous studies. The first chemical data concerning the chemistry of all the water types were published in the Gold Report (1963). Usually, only partial analyses are given (hardness, Mg^{++}, Ca^{++}, Cl^{-} and SO_4^{--} contents), while the Hydroerevna Research Company (1975), which carried out pumping tests of the wells F6, F7, F8 and F9, only reported data concerning the chemistry of the groundwater of the karstic aquifers. Finally, Karkulias (1975) published some data related to the karstic aquifers and to the river water.

In Tables 14.12 to 14.14 the average values or representative analyses of the data published are given and tentative correlations and comparisons are attempted.

The data given in the above table are in agreement with those produced by the present study (Tables 14.2 and 4). They reveal that water from aquifer 1 is of lower range ionic concentrations - especially regarding SO_4^{--} - and TDI content than is water of aquifer 2, while subzone B water generally exhibits lower ionic concentrations and TDI content than subzone A water.

Permanent changes in the ionic concentrations and TDI content of the water of the aquifers cannot be detected. Only irregular, usually small, variations are found, with the exception of the high SO_4^{--} concentrations reported by the Hydroerevna Company during the pumping tests of wells F8 and F9 (aquifer 1 subzone A) and F6 and F7 (aquifer 2).

The published data (Gold Report, 1963: Table 14.13) also show that two categories of springs can be established using the same criteria as used in the present study (Section 14.3).

The Panagia and Opiste Panagia springs actually show a much higher Mg^{++} concentration - especially when expressed as a percentage contribution to the total (used as the basic criterion) - than the other

		mgr/l										Hardness in $CaCO_3$ ppm		
		Cations					Anions							
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Total cations	Total anions	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Non permanent	Permanent	Total
1.	Aquifer 1A	81	12.1	-	-	-	-	-	16.2	13.3	-	259(?)	-	254
2.	Aquifer 1B	73	15.8	6.0	0.0	95	295	238	13.1	43.7	-	196	50	246
	Aquifer 2	96	12.6	12.9	0.6	122	355	246	18.8	90	-	202	92	294
3.	Aquifer 1A	80	11.7	5.7	1.1	99	316	282	10.7	16.8	6.9	231	16	247
	Aquifer 1B	62	13.5	7.2	0.7	83	259	230	15.6	13.8	-	187	25	212
	Aquifer 2	102	8.5	12.0	0.5	123	357	329	28	0.2	-	289	20(?)	309

Table 14.12 Chemistry of the water of the karstic aquifers (mean values)

1. Gold: Samples taken during pumping tests 7 November 1962 - 2 March 1963.
2. Hydroerevna Research Company: Samples taken during pumping tests 30 October 1975 - 9 December 1975.
3. Karkulias: Samples taken 21 December 1972 - 28 May 1973.

	mgr/l										Hardness in $CaCO_3$ ppm		
	Cations					Anions							
	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Total	Total	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Non permanent	Permanent	Total
1.	72	3.7	4.0	0.4	80	240	224	8.5	2.5	5.2	180	14	194
2.	89	10.5	4.2	0.3	101	310	291	9.6	3.1	6.2	232	25	257
3.	67	13.4	3.6	0.3	84	267	245	8.2	10.3	3.3	196	27	223
4.	75	13.6	3.8	0.3	93	294	272	8.9	9.7	3.3	217	25	242

Table 14.13 Chemical composition of the spring water (sample obtained on 16 January 1963, taken from the Gold Report, 1963).
1. Kefalovrisi 2. Korbitsi 3. Panagia
4. Opiste Panagia

springs characteristed as karstic springs. The Korbitsi spring here appears to have a high Mg^{++} content, although this value cannot be taken as representative, as it is higher than its average Mg^{++} content value of 8 mgr/l as reported in the other eight partial analyses carried out at short intervals during the same year. The springs of the Panagia group also have higher absolute values of sulphate content than the other karstic springs, a fact also pointed out during the present study.

On the other hand, the data reported also reveal that the Kefalovrisi spring has a lower range of ionic concentrations, TDI content and hardness values than the Korbitsi spring, while the Palataki spring water resembles, in its chemistry, the Korbitsi spring water. This supports facts established during the present study.

There were no significant changes in the chemical character of the water of the respective springs since 1963 (for comparisons see Tables 14.6 and 7). Most ion concentrations and TDI content remained fairly stable, while there were only small variations in the Mg^{++} and SO_4^{--} contents.

The data given in the Gold Report (1963) for springs occurring in the wider area of the basin, mainly to the west of the Kyparissia field (eg Lycosoura, Lyckaeon, Aghios Joannis at Isoma Karyes) and which, on hydrogeological evidence, issue from limestone outcrops, show that these springs present the same chemical characteristics as the karstic springs of the Kyparissia field area (ie low Mg^{++} contribution to the total cationic concentration - less than 5(?) mgr/l - and also low SO_4^{--} content - lower than 8 mgr/l).

Given the small amount of data available, only limited comparisons can be made for the water from the Alfios river because of the areal and seasonal variations in chemistry which it displays (see Section 14.4).

	mgr/l										Hardness in $CaCO_3$ ppm		
	Cations					Anions							
	Ca^{2+}	Mg^{2+}	Na^+	K^+	Total cations	Total anions	HCO_3^-	Cl^-	SO_4^-	NO_3^-	Non permanent	Permanent	Total
1.	56	11.3	8.3	0.6	76	231	209	11.4	8.9	1.8	171	15	186
2.	71	7	8.6	1.2	88	279	237	12.6	26	3	195	20	205
3.	78	10.6	8.7	0.8	98	296	240	9.9	46	0	197	40	237

Table 14.14 Chemical composition of Alfios river water (wet season mean values).
1. Gold study (sample taken at Thoknia on 17 January 1963).
2. Karkulias study (3 samples taken on 30 December 1973).
3. Present study (3 samples taken at the Kyparissia bridge on 4 February 1984).

The most striking feature of the chemical evolution of the Alfios river water since 1963 is the very high increase in the SO_4^{--} content which has, in turn, affected the permanent-hardness values. This increase must be associated with the excavation and transportation of lignite from the open pits, the disposal of sterile material and industrial activity in the area, all of which produce debris rich in S-constituents.

Other data included in the Gold (1963) and Karkulias (1975) studies concerning the water chemistry of the main tributaries (ie Elisson, Xerilas, Kutifarena, Ligataris), showed that they generally carry water with lower ionic concentrations than that of the Alfios.

By way of conclusion, it can be said that there is only a small increase in SO_4^{--} content in the natural waters studied, except for the surface water in the Alfios river, in which a much greater increase is noticed. This increase is due mainly to the power station operation which enriches the atmosphere with S-constituents (SO_2, SO_3) and, in turn, the rainwater with H_2SO_4.

14.7 Conclusions

The hydrochemical investigations provided data from which could be drawn some important conclusions which are in agreement with and, therefore, confirm the results of the other hydrogeological investigations undertaken.

The interpretations resulting from the hydrochemical investigations can be summarised as follows:

1) The water of the karstic springs of Kefalovrisi, Korbitsi and Palataki is of Ca:HCO_3 type, while the water of aquifer 1 and the Panagia and Opiste Panagia springs is of Ca/Mg:HCO_3 type and the water of aquifer 2 and the Alfios river water are of Ca/Mg: HCO_3/SO_4 type.

2) The Panagia group of springs discharge water which more closely resembles that of aquifer 1 than it does the water of the other karstic springs and is, therefore, associated with it and is

considered to arise as an overflow of aquifer 1.

3) The karstic aquifers and the spring water demonstrate almost no seasonal variability, while the Alfios river water shows great seasonal and also areal variability.

4) The small, independent, shallow aquifers developed in the basin sediments contain a very mineralised (hard) water.

5) The water moving through the recent gravel body of the Alfios river and also through the Lower and the Thoknia terraces, partly discharging through springs (those situated to the south and around the Kyparissia bridge) and partly percolating down to the aquifers, has higher ionic concentrations than the Alfios river water.

6) Aquifers 1 and 2 are almost exclusively recharged by the Alfios river/surface water (shown to be true for aquifer 2 by hydrological evidence).

7) The further the aquifer is from its recharging point from the Alfios river, the greater is the decline in the ionic concentrations.

8) There is an initial increase in the sulphate ion concentration in all natural waters of the area. This increase is high for the Alfios river and, consequently, is also high in the water of the aquifers.

Karstic groundwater is more susceptible to organic contamination than are most types of groundwater due to its movement through open fissures rather than through filtering pores. Given that the aquifers are recharged with water from the Alfios river and that the river receives the waste products from both the town of Megalopolis and from industry located nearby, the danger of organic pollution of the aquifers is constantly increasing.

PART V CONCLUSIONS

CHAPTER 15: CONCLUSIONS

The detailed geological mapping of the study area to a scale of 1:25,000 shows that it is built up of formations of the Phyllitic-Quartzitic series and of the Tripolis and Pindos geotectonic zones, while the basin is filled with unconsolidated deposits containing important lignite deposits.

The Phyllitic-Quartzitic series consists of low-grade metamorphic rocks, mainly schists and quartzites, formed in conditions of high pressure and low temperature. The formations of the Tripolis zone, which are thrust onto the Phyllitic-Quartzitic series, consist of a low-grade metamorphic basement (the Tyros beds), the carbonate series and the flysch sequence. The Tyros beds consist of low to very low-grade metamorphic rocks such as limestones/dolomites, psammitic dolomites, calcareous phyllites and phyllites. The carbonate series of thick-bedded to massive, dark-coloured, neritic, partly biogenetic and mostly bituminous dolomites, dolomitic limestones and limestones was primarily unconformably deposited on the Tyros beds although, in many places, there is a thrust contact between these units.

In the interval between the deposition of the carbonates and the flysch, there was a period of block-faulting resulting in the formation of a number of grabens and horsts. The Megalopolis basin, first formed during this tectonic event, corresponded to a graben in which a flysch sequence of varied thickness up to 500 m. was deposited. During the flysch sedimentation and prior to the overthrust of the Pindos zone, intense erosion of the carbonate rocks of the emerged horsts, such as that on the north-eastern side of the Megalopolis basin, occurred. In places, the erosion reached down to the Tyros beds, completely removing the entire carbonate sequence.

The flysch sequence of thinly-bedded alternations of sandstones, clays and silts was unconformably deposited on the carbonate series. Conglomerates, microbreccias and olistoliths or sparse pebbles occur at various stratigraphic levels within the flysch. In the lower parts of the sequence they originate from the products of the erosion of the emerged Tripolis zone horsts while, in the upper parts, they originate from both the Tripolis and Pindos zones.

A 'tectonic block' formation of varied thickness (0-200 m) occurs between the Tripolis zone and the Pindos zone. It is made up of elements from both these zones and was formed during the overthrust processes.

The Pindos zone in the area is made up of formations of the first flysch, limestones and part of the beds transitional to the flysch. The first flysch consists predominantly of massive sandstones. The limestones consist of thinly to medium-bedded, whitish-coloured micritic and sometimes biomicritic, limestones with intercalations or nodules of chert in the lower and upper parts. An intra-formational breccia horizon of a thickness of 3-8 m is present in their lower part in the area between the villages of Kourounios and Karytena. The transition beds consist of alternations of thin to platy, micritic to biomicritic limestones, black cherts and marls with fine clastic material.

In the western part of the basin, the Pindos zone occurs in the form of irregularly-repeated thrust slices, made up of first flysch and Upper Cretaceous limestones. The thrust planes dip relatively steeply, generally towards the east. In the eastern part, the Pindic nappe is built up almost exclusively of limestones, in places strongly brecciated. A gradual transition from one type of occurrence of the Pindos zone to another was recognised on the northern side of the basin.

The basin is filled with mostly unconsolidated sediments of lacustrine and fluvial origin. Three terraces and a recent gravel body are related to the river system.

The bedrock of the Kyparissia field is built up from the Pindos zone formations. Part of it was recognised to have the same type of structure as the Pindos zone occurring on the western side of the basin while the eastern part of the Kyparissia field is made up exclusively of Upper Cretaceous limestones.

The hydrological regime of the area (precipitation, evapotranspiration, temperature, relative humidity and winds) has been determined. A mean annual rainfall value of 1107 mm for the period 1962-77 was calculated for the Alfios catchment based on the rainfall records from 19 precipitation stations. The precipitation equation giving the mean annual rainfall in relation to the elevation for the Alfios catchment (after the precipitation values had been adjusted by applying Spreen's (1947) graphical correlation technique) was computed to be: precipitation (in mm) = 771 + 0.47 x elevation (in m) ($r = 0.73$). Approximately 78% of the rain falls from October to March inclusive and the remaining 22% from April to September. Approximately 60% of the rain is lost through evapotranspiration.

The Alfios river, together with its tributaries, drains a catchment of approximately 870 km^2. The drainage network of this catchment has been drawn and classified. The development and patterns of the drainage network are predominantly controlled by the structures (mainly faulting) and by the geology of the outcrops.

The average total annual rainfall over the Alfios catchment for the period 1962-77 was calculated at 967.8×10^6 m^3/year. An effective infiltration coefficient (Ie) of 55% was calculated for the Upper Cretaceous limestones. The coefficient of the total run-off of the

Alfios was calculated as 27% of the total precipitation for the period 1962-75. The Alfios river is predominantly a winter river. Its low base-flow originates from the karstic springs - overflow of the karstic aquifers and the aquifer developed in the terrace gravel-bodies. The recession period of the Alfios lasts approximately 7 months on average. A recession constant of 0.0081 for the period from April to July and of approximately 0.003 for the period from July to November was calculated.

It was not possible to calculate a hydrological balance for the Alfios catchment, since much of the groundwater, particularly from the carbonate rocks of the Tripolis zone but also from the Pindos zone limestones where they are in hydraulic continuity, discharges outside the basin.

The great variety of the hydraulic properties of the formations of which the area is built up and the complex thrust and fold relationships have resulted in a complicated hydrogeological regime. An understanding of the structure is of fundamental importance for the determination of the hydrogeology of the area since the structure controls the movement of the groundwater within the Upper Cretaceous limestones.

The hydrogeological conditions on the margins of the Megalopolis basin were investigated and the possibility of groundwater contribution laterally to the Kyparissia field was examined and excluded.

The carbonate rocks of the Tripolis zone form a deeper aquifer system than that occurring in the Upper Cretaceous limestones. The springs located at the bottom of the Lousios river valley were recognised as a probable point of discharge of the groundwater of the carbonate rocks occurring in the northern and north-eastern parts of the basin.

As a result of the structure of upthrust slices present on the western and partly on the northern sides of the basin, a number of individual lenticular karstic aquifers are developed in the Upper

Cretaceous limestone. The groundwater within these aquifers moves roughly in a N-S (S-N) direction.

On the eastern and partly on the northern sides of the basin, the Upper Cretaceous limestones, where they are overthrust onto the flysch of the Tripolis zone, discharge through karstic springs. Over large areas, the Upper Cretaceous limestones are in hydraulic continuity with the carbonate rocks of the Tripolis zone causing the groundwater of the former to percolate to the deeper aquifer system developed in the latter. The extent of the areas which the Upper Cretaceous limestones are in hydraulic continuity with the carbonate rocks of the Tripolis zone cannot be clearly defined.

Three types of aquifer are developed in the Kyparissia field. These are a) a shallow aquifer in the generally highly permeable terrace gravel-bodies associated with the surface-water (eg Alfios), b) minor aquifers in the mostly impermeable unconsolidated basin sediments, and c) the fundamentally important aquifers developed in the highly karstified limestone bedrock. The hydraulic head of the karstic aquifer is 60-70 m above the working floor of the future open lignite pit.

The distinction of five individual karstic aquifers each with a different hydrogeological regime occurring in the limestone bedrock of the Kyparissia area was based on the study of the area's geology and hydrogeology (ie hydraulic head distribution and pattern of groundwater level fluctuations) and also on the results of the hydrochemical investigation.

Aquifer 1 is the largest of these aquifers developed in the eastern part of the field. Its eastern extent cannot be well determined. Within the Kyparissia field it is confined for most of its extent. It discharges through the karstic springs located around the Kyparissia bridge and also through the springs of Panagia and Opiste Panagia as well as directly into the Alfios. Recharge takes place from the Kyparissia stream which crosses the aquifer at an elevation of 360 m to the west of the Kyparissia field and the aquifer is also in open continuity with the Alfios river in the area around the Kyparissia bridge.

Groundwater levels in this aquifer show only long term fluctuations, ie seasonal and annual. The lowest level recorded during the period of observation (1975-81) was 325-326 m (November 1977), while the highest was 339-340 m (May 1980). A rise in the groundwater level of approximately 1 m per year on average during the observation period is related to a corresponding increase in the total annual precipitation over this period. Transmissivity values were calculated at between 26 and 170 m^2/day, while the storage coefficient was calculated at between 0.0001 and 0.02. These differences in the values calculated were not considered to be due to an anisotropy of aquifer 1 but, rather, to the presence of different boundary conditions within the extent of the aquifer.

Aquifer 2 is of small extent and occurs to the north of the Kyparissia field. It is in open hydraulic continuity with the Alfios, its only source of recharge. The water table/piezometric surface in this aquifer lies at an elevation of between 325 and 329 m and the groundwater level shows no detectable significant fluctuations. Aquifer 3 is in wide hydraulic continuity with aquifer 2, while aquifers 4, 5 and 6, occurring to the west of the field, are only minor. The Mavria spring is hydrogeologically associated with aquifer 6.

Study of the hydrochemistry showed that the water from the karstic springs (ie those of Kefalovrisi, Korbitsi and Palataki) is of $Ca:HCO_3$ type, while the water from aquifer 1, the Panagia and Opiste Panagia springs is of $Ca/Mg:HCO_3$ type and the water from aquifer 2 and the Alfios river water are of $Ca/Mg:HCO_3$ type. The minor aquifers developed in the basin sediments contain a very mineralised (hard) water.

Based on the results of the hydrochemical investigation, it was further established that the Panagia and Opiste Panagia springs are hydrogeologically associated with aquifer 1 and, furthermore, that aquifers 1 and 2 are recharged predominantly from the Alfios river and other surface water.

A recent increase in SO_4^{--} content in all water bodies of the area may be due to the mining of lignite and its combustion at the Electricity Power Station just outside Megalopolis.

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APPENDICES

APPENDIX Ia

MEAN MONTHLY AND MEAN ANNUAL PRECIPITATION

OVER THE ALFIOS RIVER CATCHMENT

1962-77

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Akovos	153.1	169.0	266.4	211.6	223.6	144.0	90.7	55.2	38.4	19.9	28.9	52.8	1454
Arachamites	97.9	144.5	209.0	153.4	157.3	104.2	71.5	51.2	38.8	25.6	17.3	37.7	1108
Vytina	87.	116.	217.	152.	146.	95.	58.	49.5	40.7	41.9	19.8	42.9	1066
Ekklisoula	97	165	239	154	182	134	85	29	27	36	16	47	1211
Zoni	80.0	123.5	185	108.8	126.8	78.4	58.7	43.7	35.3	28.4	16.9	42.4	928
Karytena	83.6	125.3	212.9	132.1	130.2	81.4	58.1	33.6	31.5	24.1	24.6	35.6	972
Manaris	83.6	112.2	182.7	141.7	132.7	88.8	60.4	42.0	33.8	29.1	22.5	33.4	963
Megalopolis	79.3	118.3	177.3	115.2	114.2	72.6	53.6	37.1	27.2	21.2	15.3	32.0	863
Neochori	107.9	158.7	253.3	160.2	161.7	113.5	70.7	38.6	19.7	12.9	19.9	42.7	1160
Paparis	104.4	138	227	150	173	117	69	50.4	31.5	36.7	17.3	39.4	1154
Potamia	92.9	132.5	224.0	149.3	147.5	91.0	55.8	40.6	20.8	17.3	23.2	23.3	1018
Silimna	89.5	126.2	220.2	160.9	144.1	90.6	63.1	49.9	37.4	24.8	24.1	36.8	1068
Souli	130.8	145.7	226.7	160.9	159.4	100.0	60.3	42.5	11.0	7.6	13.6	38.6	1097
Chranoi	115.1	157.1	247.6	168.0	167.1	116.2	71.7	37.4	20.9	11.4	15.0	42.8	1170
Karatoulas	84.7	131.0	204.9	122.3	141.3	97.5	63.9	56.2	42.5	32.5	16.0	37.4	1030
Kardaras	99	143	270	213	193	138	65	49	59	49	13	32	1323
Mallota	103.3	137.1	239.2	166.6	155.3	111.0	85.7	69.9	40.6	30.5	21.8	43.7	1205
Roino	109.6	123.7	193.6	149.2	135.3	85.9	70.0	49.3	51.0	32.9	22.7	38.1	1061
Tsepelakos	96.8	144.3	229.0	170.4	161.9	107.0	66.2	50.0	47.5	37.4	19.5	43.8	1174
Mean values	99.8	137.4	222.4	154.7	155.4	103.5	67.2	46.1	34.5	27.3	19.3	39.1	1107

Appendix Ia Mean monthly and mean annual precipitation in mm over the Alfios river catchment, 1962-77.

APPENDIX Ib

MEAN MONTHLY AND MEAN ANNUAL PRECIPITATION

OVER THE ALFIOS RIVER CATCHMENT

1962-84

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Akovos	161.3	220.8	329.5	246.4	236.6	158.8	119.1	68.4	39.8	20.0	34.6	64.7	1700
Arachamites	99.1	159.5	216.9	170.0	155.1	104.4	87.1	54.4	37.1	21.7	24.4	40.4	1170
Vytina	94.	137.	219.	159.	132.	93.	71.	54.7	38.9	35.7	23.1	41.3	1099
Ekklisoula	105	191	258	182	176	132	90	42	25	35	17	45	1298
Zoni	88.6	149.2	181.8	119.0	122.4	77.1	71.6	47.3	31.5	28.1	18.7	38.4	974
Karytena	85.5	143.5	207.8	138.5	124.7	79.7	68.8	34.7	28.5	19.9	24.7	30.0	986
Manaris	89.2	130.2	186.4	146.9	128.3	87.8	71.9	44.4	29.3	26.2	22.2	33.1	996
Megalopolis	85.6	133.4	170.0	119.2	107.0	71.1	65.1	40.8	24.5	23.4	16.9	29.3	886
Neochori	116.3	187.1	255.3	172.5	160.0	111.4	89.4	45.6	22.1	14.0	18.5	41.0	1233
Paparis	112.1	167.	250.	174.	178.	133.	96.4	70.3	37.3	40.9	33.7	40.3	1333
Potamia	99.2	155.2	221.8	158.0	141.9	88.3	70.2	43.4	20.1	14.5	23.1	31.6	1067
Silimna	95.5	154.7	224.3	169.1	141.0	95.6	78.9	52.2	34.3	24.1	23.1	37.5	1130
Souli	129.0	166.4	223.6	165.6	149.3	97.0	74.1	41.7	13.6	7.2	15.8	35.0	1118
Chranoi	131.0	178.1	248.7	179.0	164.6	110.6	86.8	40.9	19.5	9.6	15.1	36.4	1220
Mean values	124.3	189.4	266.1	191.0	176.4	120.0	95.0	56.7	34.5	26.7	25.9	45.3	1351

Appendix Ib   Mean monthly and mean annual precipitation in mm over the Alfios river catchment, 1962-84.

APPENDIX Ic

ANNUAL AND MEAN ANNUAL PRECIPITATION

OVER THE ALFIOS RIVER CATCHMENT

1962/63-1983/84

Hydr. year/ Station	62/63	63/64	64/65	65/66	66/67	67/68	68/69	69/70	70/71	71/72	72/73	73/74	74/75	75/76	76/77	77/78	78/79	79/80	80/81	81/82	82/83	83/84	Mean
Akovos	1441.4	915.9	1216.	1030.1	757.9	1280.6	1397.5	1525.8	2051.0	1497.6	1351.8	2204.5	1386.3	1918.2	1831	2548.2	2416.3	2456.4	2236.7	2445.1	1746.8	1744.9	1700
Arachamites	1643.2	1236.4	1097.0	1296.	1040.	1224.7	1152.0	1331.9	954.2	900.1	980.0	963.8	862.9	1036.3	907.4	1293.0	1252.9	1512.1	1650.3	1300.8	882.2	1224.7	1170
Vytina	1627.6	1033.0	1030.9	1152.	1019.	1271.6	981.8	1214.5	1067.4	1005.1	757.4	1038.0	860.2	999.	907.	1302.8	1062.2	1368.3	1321.6	1211.9	793.0	1164.0	1099
Ekklisoula	1709.	1129.	1234.	1352.	1269.	1305.	934.1	1298.8	1111.6	1121.2	998.5	1510.3	880.9	1300.1	1007.2	1337.7	1247.2	1938.2	1858.4	1440.2	1069.0	1520.0	1298
Zoni	1429.4	898.2	905.7	986.1	1054.8	932.5	899.4	1093.1	835.5	881.3	865.0	653.0	751.2	975.1	762.9	1101.2	1157.2	1267.6	1159.5	1081.9	780.4	948.0	974
Karytena	1337.4	903.0	989.7	1007.5	996.8	995.5	976.0	1142.0	855.9	947.0	816.3	864.7	854.0	1100.	789.2	1070.4	1011.8	1090.9	989.7	1002.0	808.3	1135.0	986
Manaris	1122.	893.2	971.4	1064.0	892.7	1206.4	895.4	1019.5	877.6	990.0	927.6	881.5	764.5	1135.0	803.5	1065.5	1062.5	1197.0	1270.0	1110.5	829.5	935.5	996
Megalopolis	1292.3	809.4	920.1	933.0	824.0	930.5	797.2	983.0	781.0	886.9	788.1	703.2	663.6	945.4	693.7	888.7	1003.9	1049.0	1003.9	884.9	779.	926	886
Neochori	1310.7	874.0	1179.3	1239.3	1264.1	1282.7	1212.6	1315.2	1245.4	1076.8	1075.9	1041.5	940.4	1311.4	1026.3	1242.7	1324.0	1508.1	1476.	1530.1	1132.0	1512.3	1233
Paparis	1477.8	885.0	1063.	1333.	1149.1	1467.0	1028.0	1272.0	1216.1	1185.0	1126.3	945.6	890.2	1296.4	969.2	1420.5	1555.9	1998.4	2105.7	2060.8	1314.5	1593.1	1333
Potamia	1428.9	937.6	1181.1	1035.8	838.4	1159.3	927.6	1203.0	932.0	996.9	995	908	812.5	1010.7	908.8	1162.3	1258.5	1175.8	1344.9	1292.1	882.3	1092.5	1067
Silimna	1587.	998.0	685.2	957.	1054.3	1360.9	980.5	1267.7	1031.1	986.9	1235.6	961.0	872.9	1207.3	824.8	1214.6	1157.0	1548.4	1465.5	1332.7	914.9	1216.9	1130
Souli	1403.	1099.9	1193.6	1330.7	1109.3	1052.4	1022.5	1281.4	1051.5	1159.9	1020.2	1054.6	605.7	1154.2	921.0	1205.5	1123.2	1324.1	1289.2	1123.1	902.0	1195.	1118
Chranoi	1445.	968.4	1169.0	1292.5	1247.5	1202.9	1206.6	1251.7	1180.3	1181.7	1171.9	1032.5	897.3	1305.2	1006.7	1406.8	1347.5	1412.8	1445.4	1398.2	1032.4	1252.4	1220
Karatoulas	1393.6	1143.3	947.7	1037.3	1152.2	1179.9	1147.5	1172.0	864.3	849.6	903.8	856.7	849.6	1032.3	923.2	-	-	-	-	-	-	-	1030
Kardaras	1948.8	1344.8	1413.6	1083.8	1150.3	1383.0	1135.5	1480.	1339.6	1354.1	1478.8	1301.	1108.	1209.	1019.	-	-	-	-	-	-	-	1323
Mallota	1941.6	1107.2	1143.9	1203.7	1171.7	1178.2	1146.3	1379.5	1327.9	1069.3	1179.6	1252.9	964.5	1266.1	744.6	-	-	-	-	-	-	-	1205
Roino	1452.1	1099.3	1112.3	1034.9	930.4	1155.2	1016.0	1149.1	1010.7	1113.5	1044.5	1094.9	917.1	983.7	804.4	-	-	-	-	-	-	-	1061
Tsepelakos	1797.3	1095.6	976.6	1452.0	1041.2	1468.8	1220.	1262.5	1238.5	1056.0	986.2	1220.5	848.4	1109.3	834.4	-	-	-	-	-	-	-	1174
Mean	1515.2	1019.5	1075.3	1148.5	1050.7	1212.5	1056.6	1244.4	1103.8	1066.3	1036.9	1078.3	880.5	1173.4	930.8	1217.3	1198.7	1389.8	1374.5	1281.0	924.4	1164.0	1159/ 1140

Appendix Ic Annual and mean annual precipitation in mm over the Alfios river catchment, 1962/63-1983/84.

APPENDIX Id

DATA FOR CALCULATING THE PRECIPITATION EQUATIONS AND THE CORRELATION COEFFICIENTS

Station	Elevation of the station	Measured precipitation in mm	Computed precipitation in mm					
	x	y1	y2	x^2	$y1^2$	$y2^2$	xy1	xy2
Akovos	800	1,454	1,380	640,000	2,114,116	1,904,400	1,163,200	1,104,000
Arachamites	760	1,108	1,140	577,600	1,227,664	1,299,600	842,080	866,400
Vytina	1,010	1,066	1,170	1,020,100	1,136,356	1,368,900	1,076,660	1,181,700
Ekklisoula	630	1,211	1,050	396,900	1,466,521	1,102,500	762,930	661,500
Zoni	510	928	850	260,100	861,184	722,500	473,280	433,500
Karytena	490	972	890	240,100	944,784	792,100	476,280	436,100
Manaris	750	963	1,140	562,500	927,369	1,299,600	722,250	855,000
Megalopolis	420	863	880	176,400	744,769	774,400	362,460	369,600
Neochori	500	1,160	1,120	250,000	1,345,600	1,254,400	580,000	560,000
Paparis	760	1,154	1,160	577,600	1,331,716	1,345,600	877,040	881,600
Potamia	390	1,018	960	152,100	1,036,324	921,600	397,020	374,400
Silimna	900	1,068	1,185	810,000	1,140,624	1,404,225	961,200	1,066,500
Souli	500	1,097	1,130	250,000	1,203,409	1,276,900	548,500	565,000
Chranoi	650	1,170	1,130	422,500	1,368,900	1,276,900	760,500	734,500
Karatoulas	800	1,030	1,110	640,000	1,060,900	1,232,100	824,000	888,000
Kardaras	950	1,323	1,270	902,500	1,750,329	1,612,900	1,256,850	1,206,500
Mallota	660	1,205	1,070	435,600	1,452,025	1,144,900	795,300	706,200
Roino	1,08	1,061	1,265	1,166,400	1,125,721	1,600,225	1,145,880	1,366,200
Tsepelakos	1,000	1,174	1,140	1,000,000	1,378,276	1,299,600	1,174,000	1,140,000
Total	13,560	21,025	21,040	10,480,400	23,616,587	23,633,350	15,199,430	15,396,700
Mean	714	1,107	1,107	-	-	-	-	-

Appendix Id Data for calculating the precipitation equations and the correlation coefficient.

APPENDIX Ie

MONTHLY AND MEAN ANNUAL TEMPERATURES

AT THE MEGALOPOLIS STATION

1963-83

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
1963	7.7	8.9	8.7	12.5	15.7	21.0	24.7	25.9	22.6	16.7	13.0	10.3	15.6
1964	5.6	7.6	11.0	13.3	16.8	22.4	23.9	24.7	20.8	18.1	12.0	8.6	15.4
1965	7.6	5.6	9.4	10.9	14.7	21.0	24.8	22.8	21.7	16.1	12.4	8.9	14.7
1966	6.4	9.7	8.8	13.3	15.2	20.7	23.7	25.0	20.7	16.3	12.4	8.4	15.0
1967	6.1	5.9	9.0	12.0	16.2	19.9	23.8	24.9	20.2	16.9	12.0	8.4	14.6
1968	5.0	8.8	8.3	14.7	20.1	20.8	23.9	22.8	19.7	14.9	12.0	8.1	14.9
1969	6.3	8.6	10.0	10.7	18.0	21.5	22.2	24.0	22.1	16.2	13.4	8.3	15.1
1970	9.2	8.7	10.2	13.6	15.8	21.8	23.7	25.0	21.9	15.4	(11.1)	(8.0)	15.3
1971	6.3	6.5	7.8	11.8	16.7	19.7	20.5	22.6	18.2	12.8	10.7	8.3	13.5
1972	8.3	7.0	9.5	13.5	15.5	20.9	21.7	21.8	20.1	12.9	10.4	7.0	14.1
1973	6.0	6.5	7.4	10.3	17.1	20.6	22.9	23.4	20.3	15.4	9.9	9.1	14.1
1974	6.1	7.3	8.3	10.2	14.5	19.5	22.4	22.6	19.4	15.3	10.1	5.9	13.5
1975	5.5	5.9	9.9	12.8	16.1	19.9	22.5	21.1	20.5	14.8	10.0	7.0	13.8
1976	5.7	6.0	9.4	12.0	16.5	19.1	21.6	20.3	18.2	16.0	11.2	8.3	13.7
1977	6.5	8.8	9.7	11.1	17.6	20.0	23.6	23.1	18.1	13.7	12.0	6.3	14.2
1978	5.6	8.0	9.0	10.6	15.8	19.4	22.6	21.6	17.0	14.8	8.1	8.2	13.4
1979	5.9	8.0	10.3	10.4	15.1	19.8	21.8	21.7	19.5	15.1	10.2	7.5	13.8
1980	5.4	5.8	8.9	10.4	14.8	18.9	22.1	22.9	19.7	15.9	12.7	7.4	13.7
1981	3.9	6.2	10.7	12.7	15.3	21.0	21.6	22.7	20.1	17.0	8.3	8.9	14.0
1972	7.2	5.1	7.4	11.8	15.5	20.2	22.3	23.1	21.1	16.5	10.3	7.9	14.0
1983	5.6	5.2	8.4	13.1	17.4	18.9	22.1	21.9	20.6	15.3	11.5	8.0	14.0
Mean	6.3	7.1	9.2	12.0	16.2	20.3	22.8	23.0	20.1	15.5	11.1	8.0	14.3

Appendix Ie Monthly and mean annual temperatures in °C at the Megalopolis Station, 1962-83.

APPENDIX II

MEAN MONTHLY AND MEAN ANNUAL DISCHARGE RATES

OF THE ALFIOS RIVER

1961/62-1974/75

Hydr. year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1961-62	0.446	2.105	12.23	8.013	25.99	24.11	6.389	2.791	1.185	1.075	0.991	1.006	7.194
1962-63	1.563	19.04	42.37	14.99	32.55	16.78	11.44	8.544	4.962	3.314	2.275	1.984	13.317
1963-64	5.742	3.927	15.72	4.549	7.329	13.57	3.804	2.334	1.817	1.096	0.779	0.641	5.109
1964-65	0.510	0.680	-	-	-	11.80	12.28	7.37	2.46	1.33	0.830	0.550	-
1965-66	0.440	3.450	14.32	-	18.73	14.51	4.84	2.87	2.02	0.830	0.690	0.630	-
1966-67	0.770	-	20.44	18.89	6.39	4.76	3.48	2.13	0.810	0.580	0.380	0.390	-
1967-68	1.00	1.12	21.48	73.63	29.41	9.51	4.21	2.30	2.12	1.36	1.28	0.690	12.343
1968-69	0.990	0.830	49.55	16.40	14.47	19.66	5.79	3.21	2.06	1.28	0.890	0.700	9.653
1969-70	0.560	1.74	62.43	29.17	22.97	15.69	5.27	2.34	1.45	2.96	2.52	2.23	12.444
1970-71	1.18	1.23	4.19	6.73	22.07	30.85	8.46	3.00	1.70	1.01	0.770	0.630	6.818
1971-72	1.02	1.53	7.34	7.99	43.97	-	-	-	-	-	-	-	-
1972-73	-	-	-	-	-	-	-	-	-	-	-	-	-
1973-74	0.4227	1.992	8.165	5.806	24.03	20.60	9.945	2.872	1.177	0.6516	0.4226	0.3617	6.370
1974-75	0.6467	3.704	4.664	7.458	11.26	7.054	2.889	1.943	0.9179	0.6568	0.2597	0.2640	3.476
Mean	1.176	3.446	21.908	17.602	21.597	15.741	6.566	3.475	1.889	1.345	1.007	0.836	8.525

Appendix II Mean monthly and mean annual discharge-rates in m^3/sec of the Alfios river during the period 1961/62-1974/75.

APPENDIX III

GROUNDWATER LEVELS IN THE KYPARISSIA FIELD

1975-1981

Groundwater levels recorded in the observation wells sunk in the karstic aquifers 1 to 6
(in m above sea level)

	1975		1976			1977			1978			1979			1980		1981
Well	7/12 lower	16/5 higher	21/11 lower	- differ.	15/5 higher	13/11 lower	- differ.	14/5 higher	12/11 lower	- differ.	13/5 higher	18/11 lower	- differ.	11/5 higher	16/11 lower	- differ.	17/5 higher
								Aquifer 1									
F1	327.22	326.56*	322.98*	3.58	331.62	319.67*	11.95	329.32*	325.32*	4.00	329.86*	332.22	-2.36	-	332.22	-	-
F2	326.21	333.36	326.26*	7.10	328.70*	322.58*	6.12	336.98	-	-	336.74	329.58*	7.16	-	331.13	-	336.38*
F3	326.84	333.19	328.72*	4.47	331.29*	325.34*	9.95	336.64*	330.97	5.67	336.39*	332.24*	3.64	-	333.94	-	338.14*
F4	327.14*	333.42	327.95	5.47	331.61	325.42	6.19	336.97	331.15*	5.82	-	-	-	-	-	-	339.07*
F5	325.17*	333.41	327.91	5.50	330.43*	325.60	4.83	336.14	331.12	5.02	336.80	332.75	4.05	339.27	334.90	4.37	337.55*
F8	327.24	333.33*	329.06	4.27	331.56	325.46*	6.10	-	-	-	336.81	331.96*	4.85	339.26*	333.86	5.40	338.76*
F9	320.21*	321.51*	329.05	-7.54	322.75*	320.85*	1.90	-	322.75*	-	319.35*	320.90*	-1.55	340.05	334.25	5.79	338.95
Meg 1	327.29	333.26	328.92	4.34	331.43	325.51	5.92	337.06	331.16	5.90	337.03	332.16	4.87	339.46	334.26	5.20	338.79
Meg 2	-	333.26	328.99	4.27	331.54	325.67	5.87	337.09	331.23	5.86	337.13	332.26	4.87	339.21	334.21	5.00	338.61
P1	328.05	336.43	330.05	6.38	332.68	326.15	6.53	-	-	-	338.68	334.73	3.95	342.23	334.13	8.10	340.33
P2	-	-	341.90	-	336.80	328.79	8.01	346.81	-	-	-	341.17	-	346.37	335.47	12.10	342.82
4/3	328.02	333.65	329.51	4.14	-	-	-	-	-	-	-	-	-	-	-	-	-
P5	327.15	333.30	328.88	4.42	331.50	325.47	6.03	-	-	-	-	-	-	-	-	-	-
P6	327.19	333.29	328.90	4.39	331.76	325.42	6.34	336.54	331.17	5.37	-	332.09	-	339.19	334.09	5.10	338.49
P7	328.14	337.04	330.29	6.75	332.79	326.14	6.65	-	-	-	338.74	335.14	3.60	342.74	336.74	6.00	340.34
P8	328.40	337.38	330.58	6.80	333.00	326.57	6.43	-	-	-	338.87	335.46	3.41	342.90	336.80	6.10	340.50
P9	-	331.56	329.00	2.56	330.94	325.88	5.06	331.96	330.40	1.46	331.73	331.13	0.60	332.08	330.58	1.50	331.88

* Groundwater level recorded in the production wells when they were in operation.

	1975		1976			1977			1978			1979			1980		1981
Well	7/12 lower	16/5 higher	21/11 lower	- differ.	15/5 higher	13/11 lower	- differ.	14/5 higher	12/11 lower	- differ.	13/5 higher	18/11 lower	- differ.	11/5 higher	16/11 lower	- differ.	17/5 higher
P11	-	-	333.72	-	332.87	326.18	6.09	341.11	331.61	9.50	339.33	337.08	2.25	344.23	335.13	9.10	340.93
P16	-	-	-	-	331.57	325.47	6.10	336.60	331.17	5.23	-	331.97	-	339.07	-	-	339.07
P17	-	-	-	-	330.06	325.85	4.21	336.80	331.58	5.22	336.63	-	-	-	-	-	-
P18	-	-	-	-	-	325.69	-	336.97	-	-	-	-	-	-	-	-	-
P19	-	-	-	-	-	325.83	-	336.73	331.13	5.60	336.43	332.08	4.35	338.23	-	-	338.23
P20	-	-	-	-	-	326.48	-	339.28	331.33	7.95	337.44	333.88	3.56	340.58	335.08	5.50	339.08
P21	-	-	-	-	-	325.50	-	337.11	331.59	5.52	336.99	334.34	2.65	-	-	-	-
311	-	332.88	328.50	4.38	331.35	325.25	6.10	-	-	-	-	-	-	-	-	-	-
320	-	337.89	332.17	5.72	-	326.27	-	340.99	331.94	9.05	339.12	336.59	2.53	-	349.39	-	341.19
324	327.27	333.42	328.98	4.44	331.57	325.54	6.03	-	-	-	336.57	331.94	4.63	338.87	333.92	4.95	338.42
341	328.91	335.88	330.69	5.19	332.11	-	-	-	-	-	-	-	-	-	-	-	-
342	327.30	335.93	331.36	4.57	333.53	327.68	5.85	338.62	332.60	6.02	337.90	335.20	2.70	340.65	336.95	3.70	339.95
343	327.65	334.49	329.43	5.06	332.80	325.50	7.30	337.98	331.36	6.62	337.43	333.00	4.43	339.98	335.68	4.30	339.28
344	327.99	333.84	329.20	4.64	331.69	325.62	6.07	337.22	331.18	6.04	336.78	332.17	4.61	339.42	333.52	5.90	338.72
345	327.81	333.74	329.46	4.28	331.98	326.26	5.72	337.07	-	-	336.86	332.26	4.60	338.86	333.81	5.05	338.91
346	327.97	334.29	330.40	3.89	332.95	326.95	6.00	337.71	331.74	5.97	337.26	332.99	4.27	340.34	334.84	5.05	339.59
347	326.80	332.92	328.49	4.43	331.12	325.11	6.01	336.42	330.70	5.72	336.14	331.47	4.67	338.52	333.12	5.40	338.12
348	327.14	333.15	328.64	4.51	331.34	325.37	5.97	336.75	-	-	336.87	331.73	5.14	339.07	334.17	4.90	338.57
349	327.27	333.51	329.00	4.51	331.57	325.44	6.13	337.22	331.31	5.91	336.97	332.19	4.78	339.30	334.30	5.00	338.98
350	327.27	333.33	328.99	4.34	331.60	325.60	6.00	-	-	-	-	-	-	-	-	-	-
356	327.96	333.48	329.49	3.99	331.85	326.28	5.57	336.48	331.78	4.70	336.58	332.33	4.25	338.06	334.28	3.78	-
367	327.18	333.32	328.80	4.52	331.48	325.65	5.83	336.70	331.18	5.52	336.78	333.02	3.76	339.12	334.30	4.82	338.65

	1975		1976			1977			1978			1979			1980		1981
Well	7/12 lower	16/5 higher	21/11 lower	- differ.	15/5 higher	13/11 lower	- differ.	14/5 higher	12/11 lower	- differ.	13/5 higher	18/11 lower	- differ.	11/5 higher	16/11 lower	- differ.	17/5 higher
378	327.22	333.37	328.94	4.43	331.54	325.46	6.07	336.92	-	-	336.35	331.95	4.40	339.15	333.35	5.80	338.55
381	327.52	333.34	329.00	4.34	331.61	325.47	6.14	336.79	-	-	336.96	332.22	4.74	339.32	334.27	5.05	338.87
394	327.15	333.10	328.95	4.15	331.49	325.35	5.94	336.87	-	-	336.57	332.07	4.50	339.37	334.07	5.30	338.87
								Aquifer 2									
											(20/5)						
F6	321.61*	329.05	318.89*	10.16	328.30	316.90*	11.40	327.90	-	-	328.90	329.50	-0.60	322.45*	323.65*	-1.20	321.25*
F7	321.78*	320.75*	320.64*	0.11	320.19*	318.54*	1.65	319.69*	326.39	-7.39	326.69	327.39	0.70	317.59*	326.49	-8.90	321.19*
P10	-	322.73	322.53	0.20	322.20	325.15	-2.95	321.10	326.42	-5.32	326.95	-	-	320.15	326.75	-6.60	322.55
392	326.97	328.63	327.29	1.34	328.08	-	-	-	-	-	328.40	328.46	-0.06	326.36	328.61	-2.25	325.91
								Aquifer 3									
F8/72	323.12	329.08	320.28	8.80	328.30	317.48	10.82	325.60	320.88	4.72	328.52	329.44	-0.92	323.87	-	-	-
F10/72	321.87	329.38	319.18	10.20	328.28	316.45	11.83	323.52	319.56	3.96	328.42	329.24	-0.82	324.32	328.62	-	321.82
P12	-	-	-	-	328.43	317.03	11.04	328.40	319.73	8.67	329/00	329.35	-0.35	323.08	329.33	-6.25	322.18
								Aquifer 4									
P13	-	-	-	-	338.29	335.17	3.12	339.82	337.22	2.60	340.47	338.12	2.35	343.02	339.02	4.00	342.72
								Aquifer 5									
P15	-	-	-	-	341.94	334.04	7.09	337.33	333.54	3.79	341.63	340.49	1.14	350.34	337.49	12.85	339.39
383	339.27	340.49	341.03	-0.54	341.83	341.32(?)	-	344.65(?)	-	-	-	-	-	-	-	-	-

Well	1975 7/12 lower	16/5 higher	1976 21/11 lower	- differ.	15/5 higher	1977 13/11 lower	- differ.	14/5 higher	1978 12/11 lower	- differ.	13/5 higher	1979 18/11 lower	- differ.	11/5 higher	1980 16/11 lower	- differ.	1981 17/5 higher
									Aquifer 6								
P14	-	-	-	-	-	341.72	-	356.65	343.42	13.23	355.12	349.52	5.60	355.80	346.02	9.78	352.76

Groundwater levels recorded in aquifers developed in the basin sediments

319	337.63	338.07	337.55	0.52	-	337.35	-	-	-	-	338.15	337.75	0.40	-	-	-	-
372	359.75	360.28	-	-	331.62	361.27	-	-	-	-	-	-	-	-	-	-	-
376	339.97	337.68	336.92	0.76	336.13	336.05	0.06	336.05	322.12*	13.93	339.46	341.80	-2.34	342.08	340.95	1.13	341.95

* Groundwater level corresponding to the karstic aquifer 3.

APPENDIX IV

CHEMICAL ANALYSES

Factors for converting the concentration of the major chemical constituents of the water from meq/l to ppm

<u>Cations</u>

Calcium (Ca)	meq/l x 20.04 = ppm
Magnesium (Mg)	meq/l x 12.156 = ppm
Sodium (Na)	meq/l x 22.99 = ppm
Potassium (K)	meq/l x 39.11 = ppm

<u>Anions</u>

Bicarbonate (HCO_3)	meq/l x 61.01 = ppm
Sulphate (SO_4)	meq/l x 48.03 = ppm
Chloride (Cl)	meq/l x 35.45 = ppm
Nitrate (NO_3)	meq/l x 62.0 = ppm

Aquifer samples

	Well	F1	F2	F3	F4	F5	F6	F7	F8	F9
	Samples obtained on 4 February 1984									
Cations*	(Ca	3.80	3.56		4.04	4.04		4.52	2.60	2.88
	(Mg	1.44	1.40		1.16	1.30		0.76	1.20	1.12
	(Na	0.24	0.22		0.31	0.22		0.35	0.21	0.15
	(K	0.01	0.01		0.01	0.01		0.02	0.01	0.01
Total cations		5.49	5.19		5.52	5.57		5.65	4.02	4.16
Total anions		5.45	5.15		5.58	5.53		5.57	4.09	4.16
Anions*	(HCO_3	4.86	4.47		4.54	4.84		4.26	3.72	3.78
	(SO_4	0.24	0.43		0.68	0.32		0.99	0.17	0.18
	(Cl	0.30	0.25		0.35	0.35		0.30	0.20	0.20
	(NO_3	0.05	0.00		0.01	0.02		0.02	0.00	0.00
	Temperature**	18	18		18	18		18	18	18
	pH	8.00	7.90		7.60	7.90		7.80	7.90	7.80
	EC (μ mhos)	440	480		430	460		480	320	340
Hardness (as $CaCO_3$)	(Total	262	248		260	267		264	190	200
	(Carbonate (Alkalinity)	243	223.5		227	242		213	186	189
	(Non-carbonate	19	24.5		33	25		51	4	11

* Values in meq/l.
** Laboratory temperatures in °C under which the analyses were carried out.

Aquifer samples

		Samples obtained on 13 August 1984								
	Well	F1	F2	F3	F4	F5	F6	F7	F8	F9
Cations*	(Ca	4.00	3.60	3.60	4.04	3.76	4.56		3.04	3.00
	(Mg	1.18	1.18	1.04	1.08	1.02	0.90		0.96	1.02
	(Na	0.23	0.22	0.20	0.24	0.22	0.38		0.16	0.16
	(K	0.02	0.02	0.02	0.02	0.02	0.02		0.01	0.01
Total cations		5.43	5.02	4.86	5.38	5.02	5.86		4.16	4.19
Total anions		5.40	5.04	4.90	5.44	5.09	5.93		4.09	4.19
Anions*	(HCO_3	4.82	4.36	4.34	4.66	4.34	4.44		3.72	3.72
	(SO_4	0.25	0.29	0.24	0.27	0.25	1.05		0.17	0.26
	(Cl	0.30	0.35	0.25	0.40	0.25	0.40		0.20	0.20
	(NO_3	0.03	0.04	0.07	0.11	0.25	0.04		0.00	0.01
	Temperature**	25	25	25	25	25	25		25	25
	pH	7.45	7.50	7.50	7.50	7.55	7.65		7.65	7.65
	EC (μ mhos)	530	490	460	540	490	570		400	410
Hardness (as $CaCO_3$)	(Total	259	239	232	256	239	273		200	201
	(Carbonate (Alkalinity)	241	218	217	233	217	222		186	185
	(Non-carbonate	18	21	15	23	22	51		14	15

* Values in meq/l.
** Laboratory temperatures in °C under which the analyses were carried out.

Aquifer samples

	Samples obtained on 25 September 1984								
Well	F1	F2	F3	F4	F5	F6	F7	F8	F9
Cations* (Ca	4.00	3.60	3.56	3.88	4.12	4.68	4.88	2.64	3.12
(Mg	1.14	1.20	1.16	0.92	1.00	0.88	0.68	1.16	0.92
(Na	0.25	0.25	0.22	0.25	0.25	0.40	0.35	0.15	0.17
(K	0.02	0.01	0.03	0.01	0.01	0.03	0.02	0.01	0.01
Total cations	5.41	5.06	4.97	5.06	5.38	5.99	5.93	3.98	4.22
Total anions	5.47	5.12	5.03	5.12	5.35	6.06	6.00	4.01	4.26
Anions* (HCO_3	4.82	4.46	4.44	4.50	4.72	4.34	4.72	3.50	3.68
(SO_4	0.32	0.33	0.31	0.27	0.26	1.31	0.90	0.36	0.38
(Cl	0.30	0.30	0.25	0.35	0.30	0.35	0.35	0.15	0.20
(NO_3	0.03	0.03	0.03	0.00	0.07	0.06	0.03	0.00	0.00
Temperature**	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5
pH	7.70	7.60	7.50	7.60	7.80	7.50	7.40	7.70	7.60
EC (μ mhos)	550	510	490	510	540	610	600	420	430
Hardness (as $CaCO_3$) (Total	257	240	236	240	256	278	278	191	202
(Carbonate (Alkalinity)	241	223	222	225	236	217	236	175	184
(Non-carbonate	16	17	14	15	20	61	42	16	18

* Values in meq/l.

** Laboratory temperatures in °C under which the analyses were carried out.

Aquifer samples

		Samples obtained on 16 October 1984								
	Well	F1	F2	F3	F4	F5	F6	F7	F8	F9
Cations*	(Ca	3.92	3.76	3.68	4.40	4.00	4.40	4.64	2.80	
	(Mg	1.18	1.32	1.28	1.10	1.00	1.04	0.80	1.22	
	(Na	0.24	0.20	0.22	0.25	0.23	0.45	0.35	0.14	
	(K	0.02	0.01	0.02	0.02	0.02	0.05	0.02	0.01	
Total cations		5.36	5.29	5.20	5.77	5.25	5.94	5.81	4.17	
Total anions		5.36	5.24	5.22	5.84	5.26	5.97	5.72	4.09	
Anions*	(HCO_3	4.68	4.66	4.58	4.88	4.56	4.18	4.18	3.64	
	(SO_4	0.24	0.22	0.19	0.37	0.25	1.24	1.13	0.25	
	(Cl	0.30	0.25	0.25	0.35	0.25	0.35	0.30	0.20	
	(NO_3	0.14	0.11	0.20	0.24	0.20	0.20	0.11	0.00	
	Temperature**	23	23	23	23	23	23	23	23	
	pH	7.60	7.50	7.40	7.50	7.60	7.50	7.30	7.70	
	EC (μ mhos)	490	480	480	530	480	550	540	380	
Hardness (as $CaCO_3$)	(Total	255	254	248	275	250	272	272	201	
	(Carbonate (Alkalinity)	234	233	229	244	228	209	209	182	
	(Non-carbonate	21	21	19	31	22	63	63	19	

* Values in meq/l.
** Laboratory temperatures in °C under which the analyses were carried out.

Springs Samples

Kefalovrisi Spring

	Date	8/6/82	4/8/82	25/10/82	18/3/83	14/7/83	19/9/83	6/2/84	19/4/84	2/7/84	25/9/84	16/10/84	Mean Values
Cations*	(Ca	3.56	3.60	3.44	3.60	3.44	3.44	3.64	4.00	3.40	3.44	3.56	3.56
	(Mg	0.24	0.04	0.16	0.16	0.16	0.12	0.28	0.04	0.32	0.20	0.16	0.17
	(Na	0.18	0.21	0.23	0.23	0.25	0.15	0.22	0.17	0.26	0.17	0.15	0.20
	(K	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01
Total cations		3.99	3.86	3.85	4.00	3.86	3.72	4.15	4.22	4.00	3.83	3.88	3.94
Total anions		3.96	3.89	3.90	3.97	3.93	3.81	4.20	4.14	4.07	3.81	3.82	3.95
Anions*	(HCO_3	3.66	3.64	3.48	3.60	3.50	3.52	3.88	3.82	3.63	3.46	3.50	3.61
	(SO_4	0.02	0.03	0.07	0.11	0.13	0.14	0.11	0.10	0.08	0.10	0.09	0.09
	(Cl	0.25	0.20	0.30	0.20	0.30	0.15	0.20	0.20	0.35	0.25	0.20	0.23
	(NO_3	0.03	0.02	0.05	0.06	0.00	0.00	0.01	0.02	0.01	0.00	0.03	0.02
	Temperature**	20	20	15	26	30	18	18	24.5	27	26.5	22	-
	pH	7.40	7.60	7.40	7.70	7.70	7.50	7.60	7.80	7.80	7.50	7.40	7.60
	EC (μ mhos)	380	350	285	410	410	300	350	400	430	390	360	370
Hardness (as $CaCO_3$)	(Total	190	182	180	188	180	178	196	202	186	182	186	186
	(Carbonate (Alkalinity)	183	182	174	180	175	176	194	191	182	173	175	180
	(Non-carbonate	7	0	6	8	5	2	2	11	4	9	11	6

* Values in meq/l. ** Laboratory temperatures in °C under which the analyses were carried out.

Panagia Spring

	Date	8/6/82	4/8/82	25/10/82	18/3/83	14/7/83	19/9/83	6/2/84	19/4/84	23/7/84	13/8/84	7/4/85	Mean Values
Cations*	(Ca	3.52	3.08	3.40	3.44	3.36	3.44	3.56	3.72	3.32	3.60	3.56	3.45
	(Mg	1.10	1.32	1.06	1.02	1.08	1.08	1.08	0.92	1.16	1.00	1.06	1.08
	(Na	0.17	0.22	0.22	0.23	0.24	0.25	0.25	0.17	0.22	0.18	0.15	0.21
	(K	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total cations		4.80	4.63	4.69	4.70	4.69	4.78	4.90	4.82	4.71	4.79	4.78	4.75
Total anions		4.75	4.62	4.63	4.75	4.79	4.85	5.01	4.88	4.62	4.77	4.81	4.77
Anions*	(HCO_3	4.22	4.20	4.16	4.28	4.24	4.28	4.58	4.38	4.14	4.30	4.38	4.28
	(SO_4	0.24	0.17	0.13	0.20	0.30	0.30	0.12	0.20	0.27	0.26	0.20	0.22
	(Cl	0.25	0.25	0.30	0.20	0.25	0.25	0.30	0.30	0.20	0.20	0.20	0.25
	(NO_3	0.04	0.00	0.04	0.07	0.00	0.02	0.01	0.00	0.01	0.01	0.03	0.02
	Temperature**	20	20	15	26	30	18	18	24.5	27	25	23	–
	pH	7.30	7.50	7.60	7.60	7.70	7.50	7.70	7.50	7.60	7.50	7.25	7.50
	EC (μ mhos)	450	415	340	400	490	370	400	450	490	470	450	430
Hardness (as $CaCO_3$)	(Total	231	220	223	223	222	226	232	232	224	230	231	226
	(Carbonate (Alkalinity)	211	210	208	214	212	214	229	219	207	215	219	214
	(Non-carbonate	20	10	15	9	10	12	3	13	17	15	12	12

* Values in meq/l. ** Laboratory temperatures in °C under which the analyses were carried out.

	Korbitsi Spring				Palataki Spring					Op Panagia Spring	
Date	6/2/84	25/9/84	16/10/84	Mean Values	6/2/84	19/4/84	25/9/84	16/10/84	Mean Values	6/2/84	Mean Values
Cations* (Ca	4.68	4.60	4.80	4.69	4.00	4.80	4.56	4.56	4.48	4.76	4.76
Cations* (Mg	0.40	0.20	0.24	0.28	0.56	0.16	0.40	0.36	0.37	1.14	1.14
Cations* (Na	0.20	0.19	0.15	0.18	0.30	0.25	0.25	0.23	0.26	0.25	0.25
Cations* (K	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total cations	5.29	5.00	5.20	5.16	4.87	5.22	5.22	5.16	5.12	6.16	6.16
Total anions	5.32	4.93	5.12	5.12	4.91	5.17	5.15	5.18	5.10	6.22	6.22
Anions* (HCO_3	5.00	4.60	4.84	4.81	4.30	4.74	4.82	4.78	4.66	5.64	5.64
Anions* (SO_4	0.11	0.08	0.02	0.07	0.30	0.23	0.13	0.20	0.21	0.27	0.27
Anions* (Cl	0.20	0.25	0.15	0.20	0.30	0.20	0.20	0.20	0.22	0.30	0.30
Anions* (NO_3	0.01	0.00	0.11	0.04	0.01	0.00	0.00	0.00	0.00	0.01	0.01
Temperature**	18	26.5	22	-	18	24.5	26.5	22	-	18	-
pH	7.50	7.40	7.40	7.40	7.60	7.50	7.30	7.30	7.40	7.70	7.70
EC (μ mhos)	440	500	480	460	440	500	520	470	480	490	490
Hardness (as $CaCO_3$) (Total	254	240	252	248	228	248	248	246	243	295	295
Hardness (as $CaCO_3$) (Carbonate (Alkalinity)	250	230	242	240	215	237	241	239	233	282	282
Hardness (as $CaCO_3$) (Non-carbonate	4	10	10	8	13	11	7	7	10	13	13

* Values in meq/l. ** Laboratory temperatures in °C under which the analyses were carried out.

River water

	Date	Alfios river												Streamlet west of Kyparissia
	Date	6 February 1984			13 August 1984			25 September 1984			16 October 1984			6 February 1984
	Locations	A1	A2	A3	A1	A2	A3	A1	A2	A3	A1	A2	A3	
Cations*	(Ca	3.88	3.92	3.80	5.60	5.36	4.40	4.88	4.48	4.24	3.36	3.28	3.36	2.76
	(Mg	0.80	0.94	0.86	1.42	1.48	1.24	1.40	1.22	1.20	1.04	1.08	1.12	0.76
	(Na	0.35	0.40	0.39	0.72	0.65	0.43	0.50	0.37	0.37	0.50	0.45	0.45	0.34
	(K	0.02	0.01	0.02	0.08	0.07	0.04	0.06	0.04	0.03	0.03	0.03	0.03	0.02
Total cations		5.05	5.27	5.07	7.82	7.56	6.11	6.84	6.11	5.84	4.93	4.84	4.96	3.88
Total anions		5.10	5.29	5.15	7.82	7.62	6.20	6.76	6.01	5.77	5.01	4.83	4.91	3.99
Anions*	(HCO_3	4.05	3.94	3.82	3.16	3.60	3.66	3.02	3.84	3.46	2.62	2.46	2.80	2.99
	(SO_4	0.80	1.05	1.02	3.83	3.17	2.00	3.23	1.84	1.93	1.88	1.80	1.65	0.70
	(Cl	0.25	0.30	0.30	0.55	0.50	0.45	0.45	0.30	0.35	0.40	0.30	0.35	0.30
	(NO_3	0.00	0.00	0.01	0.28	0.35	0.09	0.06	0.03	0.03	0.11	0.11	0.11	0.00
	Temperature**	18	18	18	25	25	25	26.5	26.5	26.5	22	22	22	18
	pH	8.00	7.80	7.90	7.50	7.65	7.80	7.50	7.80	7.40	8.10	8.40	7.60	7.90
	EC (µ mhos)	420	430	410	770	740	600	690	620	590	470	460	470	330
Hardness (as $CaCO_3$)	(Total	234	243	233	351	342	282	314	285	272	220	218	224	176
	(Carbonate (Alkalinity)	202.5	197	191	158	180	183	151	192	173	131	123	140	149.5
	(Non-carbonate	31.5	46	42	193	162	99	163	93	99	89	95	84	26.5

* Values in meq/l. ** Laboratory temperatures in °C under which the analyses were carried out.

Mean values of the analyses

	Aquifer 1, subzone A (samples obtained from wells F1 to F5)					Aquifer 1, subzone B (samples obtained from wells F8 and F9)				
Date	4/2/84	13/8/84	25/9/84	16/10/84	Mean Values	4/2/84	13/8/84	25/9/84	16/10/84	Mean Values
Cations* (Ca	3.86	3.80	3.83	3.95	3.86	2.74	3.02	2.88	2.80	2.86
(Mg	1.32	1.10	1.08	1.17	1.17	1.16	0.99	1.04	1.22	1.10
(Na	0.25	0.22	0.24	0.23	0.23	0.18	0.16	0.16	0.14	0.16
(K	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Total cations	5.44	5.14	5.17	5.37	5.28	4.09	4.17	4.10	4.17	4.13
Total anions	5.43	5.17	5.22	5.38	5.30	4.13	4.14	4.14	4.09	4.12
Anions* (HCO_3	4.68	4.50	4.59	4.67	4.61	3.75	3.72	3.59	3.64	3.67
(SO_4	0.42	0.26	0.30	0.25	0.31	0.18	0.21	0.37	0.25	0.25
(Cl	0.31	0.31	0.30	0.28	0.30	0.20	0.20	0.18	0.20	0.20
(NO_3	0.02	0.10	0.03	0.18	0.08	0.00	0.01	0.00	0.00	0.00
Temperature**	18	25	26.5	22	-	18	25	26.5	22	-
pH	7.85	7.50	7.64	7.52	7.63	7.85	7.65	7.65	7.70	7.71
EC (μ mhos)	455	500	520	490	490	330	405	425	380	385
Hardness (as $CaCO_3$) (Total	259	245	246	257	252	195	200	197	201	198
(Carbonate (Alkalinity)	234	225	230	234	231	187	185	179	182	183
(Non-carbonate	25	20	16	23	21	8	15	17	19	15

* Values in meq/l.   ** Laboratory temperatures in °C under which the analyses were carried out.

	Aquifer 2 (samples obtained from wells F6 and F7)					Alfios river (samples obtained from locations A1 to A3)				
Date	4/2/84	13/8/84	25/9/84	16/10/84	Mean Values	4/2/84	13/8/84	25/9/84	16/10/84	Mean Values
Cations* (Ca	4.52	4.56	4.78	4.52	4.59	3.87	5.12	4.53	3.33	4.21
(Mg	0.76	0.90	0.78	0.92	0.84	0.87	1.38	1.27	1.08	1.15
(Na	0.35	0.38	0.38	0.40	0.38	0.38	0.60	0.41	0.46	0.46
(K	0.02	0.02	0.02	0.03	0.02	0.02	0.06	0.04	0.03	0.04
Total cations	5.65	5.86	5.96	5.87	5.83	5.14	7.16	6.26	4.91	5.86
Total anions	5.57	5.93	6.02	5.85	5.84	5.18	7.21	6.18	4.92	5.86
Anions* (HCO_3	4.26	4.44	4.53	4.18	4.35	3.93	3.47	3.44	2.68	3.38
(SO_4	0.99	1.05	1.10	1.19	1.08	0.96	3.00	2.33	1.78	2.01
(Cl	0.30	0.40	0.35	0.33	0.35	0.28	0.50	0.36	0.35	0.37
(NO_3	0.02	0.04	0.04	0.15	0.06	0.00	0.24	0.04	0.11	0.10
Temperature**	18	25	26.5	22	-	18	25	26.5	22	-
pH	7.80	7.65	7.45	7.40	7.58	7.90	7.65	7.57	8.03	7.79
EC (μ mhos)	480	570	605	545	550	420	700	630	470	555
Hardness (as $CaCO_3$) (Total	264	273	278	272	272	237	325	290	220	268
(Carbonate (Alkalinity)	213	222	226	209	218	197	174	172	131	168
(Non-carbonate	51	51	52	63	54	40	151	118	89	99

* Values in meq/l. ** Laboratory temperatures in °C under which the analyses were carried out.